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Jani Puttonen

Mobility Management in Wireless Networks

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ABSTRACT

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This dissertation discusses mobility management in IP based wireless environments. Mobility management can include both handovers within one technology and selection of access technology in a heterogeneous overlapping environment. IETF has standardized Mobile IP and its IPv6 version for handling mobility management in the IP networks. Even though Mobile IPv6 handles mobility in an application transparent way, several unresolved problems remain. This dissertation focuses on minimizing the Mobile IPv6 handover delays and interface selection in heterogeneous wireless environments.

An enhancement called Flow-based Fast Handover for Mobile IPv6 is presented for speeding up the Mobile IPv6 address registration phase. The address registration phase, and thus also packet loss, can be notably decreased. More importantly, the delay is not dependent on the distance of the Corresponding Nodes as is the case with Mobile IPv6. In addition, mechanisms to control Mobile IPv6 handovers to offer the users and applications a best access were researched. Real time information about the link status and quality as well as user preferences are taken into account in the interface selection. The objective is to offer an Always Best Connected access to the user, and seamless handovers.

Keywords: Next generation networks, 4G, IP mobility management, Mobile IPv6, handover, overlay networks, all-IP, ns-2, MIPL

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LIST OF PUBLICATIONS AND AUTHOR CONTRIBUTIONS

[PI] M. Sulander, T. Hämäläinen, A. Viinikainen, and J. Puttonen. Flow-based Fast Handover Method for Mobile IPv6 Network. Proceedings of the 59th IEEE Vehicular Technology Conference, volume 5, pp. 2447–2451, May 2004.

[PII] J. Puttonen, A. Viinikainen, M. Sulander, and T. Hämäläinen. An Analysis of the Flow-based Fast Handover Method for Mobile IPv6 Network. Proceedings of the 1st International Conference on E-Business and Telecommunication Networks, volume 3, pp. 187–190, August 2004.

[PIII] J. Puttonen, A. Viinikainen, M. Sulander, and T. Hämäläinen. Performance Evaluation of the Flow-based Fast Handover Method for Mobile IPv6 Network. Proceedings of the 60th IEEE Vehicular Technology Conference, volume 6, pp. 4437–4441, September 2004.

[PIV] J. Puttonen, H. Suutarinen, T. Ylönen, A. Viinikainen, M. Sulander, and T. Hämäläinen. Flow-based Fast Handover Performance Analysis in Mobile IPv6 for Linux Environment. Proceedings of the 61st IEEE Vehicular Technology Conference, volume 4, pp. 2575–2579, May 2005.

[PV] J. Puttonen, A. Viinikainen, M. Sulander, and T. Hämäläinen. A Fast Handover Method for Mobile IPv6 Networks. Journal of Internet Technology, Special Issue on Heterogeneous IP Networks, volume 6, number 3, pp. 305–312, July 2005.

[PVI] T. A. Ghebregziabher, J. Puttonen, T. Hämäläinen, and A. Viinikainen. Security Analysis of Flow-based Fast Handover Method for Mobile IPv6 Networks. Proceedings of the 20th IEEE International Conference on Advanced Information Networking and Applications, volume 2, pp. 849–853, April 2006.

[PVII] A. Viinikainen, S. Kaščák, J. Puttonen, and M. Sulander. Fast Handover for Upstream Traffic in Mobile IPv6. Proceedings of the 62nd IEEE Vehicular Technology Conference, volume 2, pp. 802–806, September 2005.

[PVIII] A. Viinikainen, J. Puttonen, M. Sulander, T. Hämäläinen, T. Ylönen, and H. Suutarinen. Flow-based Fast Handover Method for Mobile IPv6 Environment - Implementation and Analysis. Computer Communications, More than a Protocol for Next Generation Internet, volume 29, issue 16, pp. 3051–3065, October 2006.

[PIX] J. Puttonen, G. Fekete, P. Rybczyk, and J. Narikka. Practical Experimentation of Mobile IPv6 in Heterogeneous Environment. Acta Electrotechnica et Informatica, volume 6, number 1, pp. 31–36, 2006.

[PX] J. Puttonen, G. Fekete, J. Mäkelä, T. Hämäläinen, and J. Narikka. Using Link Layer Information for Improving Vertical Handovers. Proceedings of the 16th IEEE International Symposium on Personal Indoor and Mobile Radio Communications, volume 3, pp. 1747–1752, Sepember 2005.

[PXI] J. Puttonen and G. Fekete. Interface Selection for Multihomed Mobile Hosts. Proceedings of the 17th IEEE International Symposium on Personal Indoor and Mobile Radio Communications, September 2006.

[PXII] E. Wallenius, T. Hämäläinen, T. Nihtilä, J. Puttonen, and J. Joutsensalo. Simulation Study on 3G and WLAN Interworking. IEICE Transactions on Communications, volume E89-B, number 2, pp. 446–459, 2006.

The very first idea of the Flow-based Fast Handover for Mobile IPv6 (FFHMIPv6) method is presented in publication [PI] for improving the handover delay of Mobile IPv6. Theoretical analysis in the "best" and "worst" scenarios (i.e. network topologies) and comparison to basic Mobile IPv6 and Hierarchical Mobile IPv6 are presented. Handover delay simulation results with Network Simulator 2 (ns-2) are presented for basic FFHMIPv6 operations in publications [PII] and [PIII]. In publication [PII] the FFHMIPv6 is analyzed and compared against basic Mobile IPv6 in the "best" and "worst" scenarios to verify the results from theoretical analysis. The FFHMIPv6 is simulated by iterating different distances between the MN and other communication parties (i.e. Home Agent, Corresponding Node) using User Datagram Protocol (UDP) and Transmission Control Protocol (TCP) based applications in publication [PIII]. In addition to Mobile IPv6, the FFHMIPv6 is compared against Hierarchical Mobile IPv6. The author contributed in publications [PI], [PII] and [PIII] by implementing the FFHMIPv6 method into ns-2 simulator and performing the simulations. The design of the simulation scenarios and result analysis were done in co-operation with the other co-authors.

The FFHMIPv6 method is analyzed in real live network environment in publication [PIV]. The network is built on top of Linux Operating System (OS) and MIPL (Mobile IPv6 for Linux) Mobile IPv6 implementation. The distance of the CN is varied with UDP based Constant Bit Rate (CBR) and Voice over IP (VoIP) applications. Also, the processing delay and scalability issues induced by FFHMIPv6 method are discussed. The FFHMIPv6 studies both in simulative and real network environment with comparison to basic Mobile IPv6 are summed up and compared against other existing Mobile IPv6 enhancements in publication [PV]. In publications [PIV] and [PV] the author contributed by designing both the simulative and actual network testing scenarios, performing the ns-2 simulations, assisting in implementing and testing the FFHMIPv6 Linux implementation and analysing results.

If FFHMIPv6 is to be the primary mechanism for handover in All-IP networks it has to be a secure, efficient, and reliable alternative to the existing handover mechanisms. Any enhancements of Mobile IPv6 should not compromise the security of the existing system. The security analysis and assessment of FFHMIPv6 are presented in publication [PVI] and also some preliminary solutions are proposed. The author contributed by analyzing the FFHMIPv6 security issues and assisting in inventing possible security solutions.

To enable also fast upstream connectivity in FFHMIPv6, an enhancement is proposed in publication [PVII]. The FFHMIPv6 upstream and downstream were simulated in a ns-2 simulator in a hierarchical environment and with different UDP based applications. The author contributed by assisting in the FFHMIPv6 upstream design as well as designing the simulation scenarios and upstream implementation. In publication [PVIII] the FFHMIPv6 studies from theoretical, simulative and real-life test environment research are summed up. Both downstream and upstream studies as well as security aspects are included. The author contributions consisted of work similar to that in previous publications, including mainly simulative studies, design of all analysis scenarios, and result analysis.

The basic Mobile IPv6 is analyzed in a heterogeneous multi-access environment by means of live Linux based network environment (MIPL) in publication [PIX]. The author contributed by designing the analysis scenarios and analyzing the results. The author also assisted in building the network scenario and testing. Both the handover performance and interface selection aspects are analyzed. The usage of link layer information is presented to assist in vertical Mobile IPv6 handovers in publication [PX]. An architecture of a software (i.e. Link Information Provider) to gather up the link layer information from each link technology is presented and both the performance and interface selection aspects were discussed through a real-life use case. The author contributed by studying the link layer parameters and their utilization in the context of vertical handovers. The author also designed and performed the use case testing.

An analysis of interface selection procedures in a multihomed mobile host was performed by means of Matlab simulations in publication [PXI]. The interface selection procedure of VERHO is presented and different algorithms of preference value calculation are analyzed. The author designed the simulation scenarios in co-operation with the co-author and performed the Matlab simulations as well as the result analysis.

To enable Quality of Service in multi-access environments, 3G and IEEE 802.11e Quality of Service (QoS) integration is studied in both Differentiated and Integrated Services Quality of Service (QoS) enabled core networks by means of ns-2 simulations in publication [PXII]. The author contributed by reviewing the earlier 3G and Wireless LAN QoS research work and by analyzing the results.

CONTENTS

ACRONYMS

2G	2nd Generation
3G	3rd Generation
3GPP	3rd Generation Partnership Project
4G	4th Generation
AAA	Authentication Authorization Accounting
AH	Authentication Header
AP	Access Point
APM	Access Point Module
APr	Adaptation Proxy
AR	Access Router
B3G	Beyond 3G
BACK	Binding Acknowledgment
BS	Base Station
BU	Binding Update
CARD	Candidate Access Router Discovery
CBR	Constant Bit Rate
CDMA	Code Division Multiple Access
CN	Corresponding Node
CoA	Care of Address
CR	Crossover Router
DiffServ	Differentiated Services
DNA	Detecting Network Attachments
DSCP	DiffServ Code Point
DVB-H	Digital Video Broadcasting - Handheld
EDCF	Enhanced Distributed Co-ordination Function
ESSID	Extended Service Set Identifier
ETSI	European Telecommunications Standards Institute
FBACK	Fast Binding Acknowledgment
FBU	Fast Binding Update
FFHBU	Flow-based Fast Handover Binding Update
FFHMIPv6	Flow-based Fast Handover for Mobile IPv6
F-HMIPv6	Fast Handovers for Hierarchical Mobile IPv6
FMIPv6	Fast Handovers for Mobile IPv6

FN	Foreign Network
GPRS	General Packet Radio Service
GPS	Global Positioning System
GRA	Grey Relational Analysis
GSM	Global System for Mobile communication
HA	Home Agent
HIP	Host Identity Protocol
HMIPv6	Hierarchical Mobile IPv6
HN	Home Network
HofA	Hand-of-Address
HSDPA	High Speed Downstream Packet Access
HSUPA	High Speed Upstream Packet Access
HTML	Hypertext Markup Language
HTTP	Hypertext Transfer Protocol
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force
IMS	IP Multimedia System
IntServ	Integrated Services
IPC	Interprocess Communication
IPSec	IP Security
IP-TV	Internet Protocol Television
IRTF	Internet Research Task Force
ISE	Interface Selection Engine
IST	Information Society Technologies
L2	Layer 2
L3	Layer 3
LAC	Link Access Controller
LCoA	on-Link Care of Address
LIP	Link Information Provider
LM	Link Module
LTE	Long Term Evolution
MAC	Medium Access Control
MADM	Multiple Attribute Decision Making
MAP	Mobility Anchor Point

MEW	Multiplicative Exponent Weighting
MIB	Management Information Base
MIP	Mobile IP
MIPL	Mobile IPv6 for Linux
MIPv6	Mobile IPv6
MMP	Mobility Management Protocol
MN	Mobile Node
MS	Multimedia Streamer
NAACK	Neighbor Advertisement Acknowledgment
NAR	New AR
NAT	Network Address Translation
NEMO	Network Mobility
NGN	Next Generation Networks
NS	Neighbor Solicitation
NSIS	Next Steps in Signaling
OS	Operating System
PAR	Previous AR
PDA	Personal Digital Assistant
PDP	Packet Data Protocol
PE	Policy Engine
PHB	Per Hop Behavior
PoA	Point of Attachment
QoS	Quality of Service
RA	Router Advertisement
RCoA	Regional Care of Address
RO	Route Optimization
RPC	Remote Procedure Call
RR	Return Routability
RRM	Radio Resource Management
RSVP	Resource Reservation Protocol
RTCP	Real-time Control Protocol
RTP	Real-time Transport Protocol
RTSP	Real-time Streaming Protocol
RTT	Round Trip Time

SAW	Simple Additive Weighting
SCTP	Stream Control Transmission Protocol
SDR	Software Defined Radio
SIMA	Simultaneous Multiple Access
SIP	Session Initiation Protocol
SNMP	Simple Network Management Protocol
SNR	Signal to Noise Ratio
STP	Spanning Tree Protocol
TCP	Transmission Control Protocol
TOPSIS	Technique for Order Preference by Similarity to the Ideal Solution
TOS	Type of Service
UDP	User Datagram Protocol
UMA	Unlicensed Mobile Access
UMTS	Universal Mobile Telecommunications System
VBR	Variable Bit Rate
VERHO	Vertical Handovers in 4G System
VoIP	Voice over IP
WLAN	Wireless Local Area Network
WPAN	Wireless Personal Area Network
WWAN	Wireless Wide Area Network

LIST OF SYMBOLS

A^*	Ideal solution
A^-	Negative-ideal solution
C	Relative closeness
d	Distance metric
I	Interface vector
p	Number of attributes
q	Number of links
r	An element of the decision matrix
R	Decision matrix
S	Selected interface
t	time or round
w	Weight

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1 INTRODUCTION

In the last few years the number of mobile devices as well as access technologies have increased and the number devices are expected to increase with growing speed. The number of cellular subscribers have been increasing in an exponential rate since the beginning of 1990's and even more accelerated growth is expected with the 3G networks [11]. More importantly, it is expected that within three to five years the mobile devices will have several accesses to a variety of services. Actually, even nowadays the most advanced mobile phones have integrated IEEE (Institute of Electrical and Electronics Engineers) 802.11b/g and Bluetooth interfaces in addition to the traditional cellular interfaces. However, the unlicensed technologies are currently used and mainly for data services. New cellular phones are having more and more features and new Personal Digital Assistants (PDAs) are equipped with cellular connections, thus the development trend is toward a combination of these, a type of smartphone. In the future there will be three major alternatives for mobile device OS; Symbian, Microsoft Mobile and Linux. The Symbian operating system for mobile phones with its open Application Programming Interfaces (API) has given a boost to software development for mobile devices in the past five years, and these applications again attract more consumers. New applications such as Voice over IP (VoIP) (e.g. Skype, Session Initiation Protocol (SIP) based clients), Internet Protocol Television (IP-TV) or Digital Video Broadcast - Handheld (DVB-H) might be the drivers for handheld multimedia devices. Now, the open Linux operating system is being adapted to mobile devices opening doors to open software development. Nokia's first commercial Linux based mobile gadget Nokia 770 is a good example of this.

Different access technologies can be divided into three categories, mainly according to the size of the coverage area and bandwidth. Wireless Wide Area Networks (WWAN) has a coverage from few hundred meters to tens of kilometers, depending among other things on the subscriber density. Cellular networks (e.g. Global System for Mobile communication, GSM and the packet switched General Packet Radio Service, GPRS) can provide almost complete coverage, for example in Finland. Now, the 3rd Generation (3G) (i.e. Universal Mobile Telecommunications System, UMTS) and HSDPA (High Speed Downstream Packet Access) cellular networks are following the widely used 2nd Generation (2G) GSM network. Also HSUPA (High Speed Upstream Packet Access) and 3G Long Term Evolution (LTE) are in the specification stage. 2G cellular access networks were optimized for circuit-switched voice, while bursty data communications have been taken more into consideration since the introduction of 3G [76]. Besides the cellular networks, the IEEE 802.16 (i.e. WiMAX) standard might come into more broad use in the WWAN scope. Nevertheless, WiMAX is generally thought of as the next evolution of IEEE 802.11 WLAN networks, thus it is not seen as a competitor against the next generation of cellular networks.

Wireless Local Area Networks (WLAN) refer to technologies with a coverage from 10 to few hundred meters. IEEE 802.11 series (e.g. 802.11a/b/g) WLAN technologies [42] are getting more and more popular especially for creating hotspot Access Points (APs). Other WLAN standards, such as European Telecommunications Standards Institute's (ETSI) HiperLAN, have not become that popular. When compared to WWAN technologies, the WLAN technologies offer currently more bandwidth, but at the expense of increased power consumption and smaller coverage. Wireless Personal Area Networks (WPAN) are technologies for short range communication (max 10 meters), and include IrDA and Bluetooth. These are mainly seen as machine to machine communication technologies and rather less as access technologies, even though they can be utilized for access as well.

A term wireless overlay network was first introduced in [49]. This reflects the prediction that several access technologies will co-exist in the future and their coverage areas will overlap. The term overlay relates to overlapping networks, where WWAN, WLAN and WPAN networks comprise the different layers of access technologies. Also, the access technologies will have different characteristics related to several technology specific parameters, such as Quality-of-Service (e.g. delay, jitter), bit rate, coverage area, cost, power consumption and security [31]. Figure 1 explains the wireless overlay networks and vertical vs. horizontal mobility. For example, at time *t* the user is able to choose between WWAN and WLAN networks. It is generally thought that no access technology will or even can be superior to other technologies, if we consider several technology parameters as well as users and applications with different needs and requirements. No access technology will meet all the demands of modern communication due to possibly partly conflicting characteristics of access technologies as well as physical restrictions, maintenance, deployment costs, etc. Rather, the access technologies of different characteristics are converging into one heterogeneous, but ubiquitous access network, where different access technologies with different parameters complement each other [33]. We refer to these kinds of networks as the 4th Generation networks (4G) (or Next Generation Networks, NGN). Researchers also talk about Beyond 3G (B3G) when referring to the next technological generations to follow the third generation cellular systems [107], [45].

Heterogeneous converging networks bring out some benefits for the user and the operator. Different consumers (and of course their applications) may have different preferences related to the access technologies in use as well as their

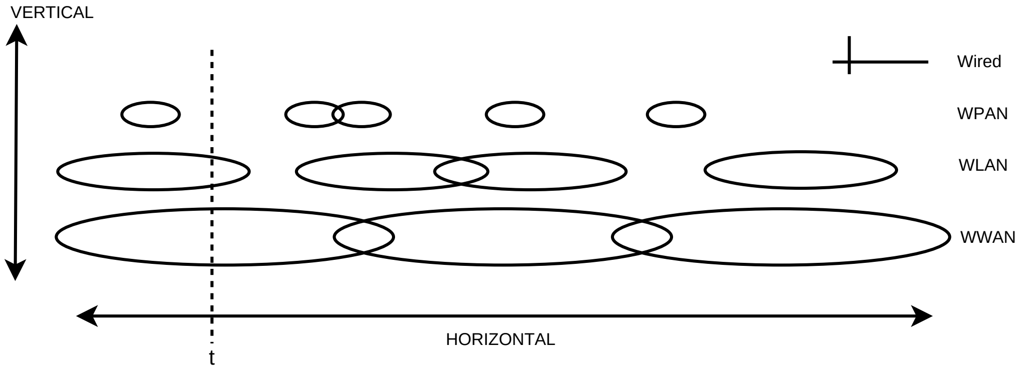

FIGURE 1 Overlay network

characteristics. Overlay networks enable Always-Best-Connected (ABC) access [35] to consumers with different preferences. Connection reliability (i.e. ubiquitousness) increases when there are several available links to choose from (also backup links are available in case of service disruptions) and when used simultaneously the user can benefit from increased throughput. Also, different accesses are suitable for different kinds of traffic, thus the applications can benefit from using the most suitable access facility for them. The operator can provide the user an increased coverage due to several accesses (e.g. indoors or rural areas) and possibly utilize load balancing in rush hours.

As discussed above, the 4th generation networks bring out many benefits to all service chain partners, such as the consumer, content provider and operator. Heterogeneous networks have already been studied about a decade, but still there exist a lot of open questions and research challenges. These are discussed more detail in the next subsection.

1.1 Vision and research challenges of the 4G wireless system

Several researchers have visioned the 4th generation networks in the past few years and several roadmaps (e.g. [3]) forecasting future circumstances have been published to predict the future to support companies, research organizations and standardization bodies in making correct strategic decisions, etc.

As discussed earlier, fourth generation communication system in general is thought of being a combination of technologies with different characteristics. References [40], [108], [91], [9] and [11] discuss related visions and research challenges. The key features of 4G networks are

- High usability – access anywhere, anytime and with any technology
- Support for multimedia services at low cost – access and communication speed

- Personalization
- Integrated services – Quality of Service

4G networks will be entirely packet switched systems, thus also core networks of cellular systems are evolving to become entirely packet switched based on IP protocol [26]. IP Multimedia Subsystem (IMS) standardized in 3rd Generation Partnership Project (3GPP) release 5 is the first practical step towards IP based service provision and 3G Long Term Evolution will provide only the packet switched core [26]. IP is generally thought of being the integration layer for all the access technologies and also for applications [9]. The term All-IP (or Native IP) refers to the integrating nature of Internet Protocol [76]. Also voice communication is evolving towards IP connectivity with the success of VoIP technologies; Session Initiation Protocol (SIP) [95] being most likely the enabling technology. Every kind of content has to be able to be accessed with good quality (or diverse set of qualities) and at a reasonable cost anywhere, anytime and with any technology, and without compromising service security.

Finally, the technology-centric approach of communication system design is likely to turn into user-centric approach. The preferences and demands of diverse users need to be met with customized personal services. The technology is hidden in the background and the user can just enjoy the services. Related to ubiquitous computing, [118] the term disappearing hardware is used; the devices and technologies will be so easy to use that people will hardly notice them.

The above discussed vision brings many research challenges with it. Here we focus on the challenges above the 3rd OSI layer; link technology specific challenges (e.g. adaptive coding/modulation, multiple antenna technologies, etc.) are mostly out of scope. For example [40] divides the research challenges into the areas of mobile station, system, and service.

Multimode mobile terminals are designed for utilizing efficiently and intelligently utilizing several interfaces of (most likely) different technologies. A software defined radio (SDR) concept [14] caused quite a lot of hype a few years ago. In SDR the device has only one transmitter/receiver which is configured according to each available technology. In this dissertation we focus on the former case, where each technology is utilized with an own optimized transmitter/receiver pair.

Terminals need to be capable of discovering different wireless systems (i.e. scanning). Traditional technology specific scanning mechanisms might not be enough for selecting the best usable link at each point of time. This introduces as well the term Always-Best-Connected (ABC) [35]. The decision of the best link is dependent on many parameters, thus what is the sufficient level of complexity for optimal decisions? ABC might stand for slightly different things depending on viewpoints, e.g. that of on operator, user and service provider [22]. In this dissertation we consider the ABC mainly from the user point of view, even though some operator preferences are shortly presented. Reference [85] discusses different enabling technologies to provide the ABC. These include different protocol stack enhancements, mobility support and End-to-End Quality of Service (QoS) support.

From the system point of view, efficient mobility and location management of the mobile devices is important. Mobile IP (MIP) [46] solves this problem quite successfully. But the increase in system load caused by handover processes, high handover latency and packet losses require some improvements. Also heterogeneous networks induce some additional problems related to multihoming, vertical handovers and simultaneous multiple access. Moving networks (Network Mobility, NEMO) introduce some additional research challenges to the mobility management protocol [91]. End-to-End Quality-of-Service (QoS) requires access technology independent QoS procedures. Basically IP or above layer QoS architectures (e.g. differentiated or integrated services) or possibly mapping procedures with different QoS mechanisms are needed [85], [91]. The traditional transport layer protocols, such as Transport Control Protocol (TCP) or User Datagram Protocol (UDP), might not be the best candidates when unreliable wireless links are used. Security and privacy solutions need to be flexible in dealing with various technologies and devices (varied capabilities, processing powers, security needs, etc). Also, technology dependent solutions might not be the most suitable ones, some upper layer solutions might be more feasible instead. Single sign-on to the network is needed. In system level also fault tolerance must be solved (e.g. hierarchical system or overlapping network) to provide adequate QoS for the user [40].

In the future a consumer will no longer be dependent on any single provider; he might be a customer to several of them, even using their services simultaneously. To meet this prospect, new business architectures, accounting procedures and accounting data maintenance is needed. Also, for the operator new ways of gathering the surplus is needed because of the increasing usage of unlicensed networks. Service based approach seem to be the view currently favoured. Traditional billing systems (technology and transaction dependent) might become old-fashioned.

1.2 Problem statement

As we noticed from the research challenges induced by the 4th generation mobile networks, the related research playground is very large. The related research problems we are focusing in this dissertation are

1. Mobile IPv6 handover performance in both horizontal and vertical handover cases and
2. Always-Best-Connected access for the user and applications in heterogeneous overlay networks.

Mobile IPv6 [46] handles the IP mobility management in an application transparent way, thus the applications are unaware of the links in use and of possibly occurring handovers. The application flows (and possible transport layer connections) do not break even though the Mobile Node (MN) is moving between IP subnets. But the procedures related to the handovers result in a time period during which the MN cannot send or receive data. This handover (or handoff) delay causes packet loss or packet retransmissions (in case of reliable transport protocols). The objective is to minimize the delay to offer the applications not only unbreakable connections but seamless connections as well.

Where the MN has multiple interfaces (and links) and several of those links are up and running, one has to choose which interface to use. Usually the MIPv6 implementations have some static priority for each interface, where the interface with highest priority is chosen. However, this is not sufficient for users with different preferences or for applications with different demands in heterogeneous environments. The objective is to find ways to provide Always-Best-Connected access for different users with minimum user intervention.

1.3 Related research projects and standardization

There exists several related projects, both within and outside the standardization bodies, which study the field of IP mobility management to fulfill the needs of heterogeneous wireless environments. The focus in here is Mobile IPv6 related work, thus other mobility management mechanisms and their related research, such as Host Identity Protocol (HIP) [73] or Session Initiation Protocol (SIP) [95] are acknowledged but out of scope. Mobility management protocols in different protocol layers and their comparisons have been presented in [37] and [29].

The Internet Engineering Task Force (IETF) standardized the Mobile IP protocols in one of its charters, the Mobile IPv6 in *Mobility for IPv6 (mip6)* charter in June 2004. Since then several IETF and Internet Research Task Force (IRTF) charters have been working on enhancing the MIPv6 functionality, with performance, reliability, multihoming, etc. in mind. The *MIPv6 signaling and Handoff Optimization (mipshop)* charter [63] concentrates on improving the MIPv6 handover performance and has produced so far for example Hierarchical Mobile IPv6 [100] and Fast Handovers for Mobile IPv6 [54] RFCs. The IRTF charter *IP Mobility Optimizations (MobOpts)* [66] focuses on topics similar to those of mipshop. Current research topics include MIPv6 route optimization, fast re-authentication mechanisms in handover situations, next Point of Attachment (PoA) selection mechanisms, etc. The *Detecting Network Attachment (dna)* charter [21] works on improving the IP layer (L3) movement detection. The link layer (L2) handover may or may not result in an IP subnet change, thus there needs to be reliable and fast mechanisms to detect the IP layer movement to be able to stay reachable. The *Network Mobility (nemo)* [75] charter enhances Mobile IPv6 protocol to support moving networks instead of pure MNs. Instead of the MN a mobile network is changing its point of attachment creating several additional research challenges. Multihoming and multiple interfaces for Mobile IPv6 are researched in the IETF

Mobile Nodes and Multiple Interfaces for IPv6 (monami6) [67] charter. Application flows can be redirected between interfaces or even used simultaneously in a MN with several interfaces, most likely of different technologies. The main benefits in this are enhanced reliability due to backup interfaces, increased bandwidth usage, load balancing, etc. Currently, the *Link Implication for End-to-End System* (LIES) charter is being started to study and define the parameters and signaling protocols aimed at link layer information delivery across interested entities (e.g. protocol layers, applications, network nodes).

The IEEE 802 working groups have traditionally focused on different access technologies, such as IEEE 802.3 Ethernet, IEEE 802.11 WLAN (WiFi), IEEE 802.15 WPAN and IEEE 802.16 broadband wireless access (WiMAX). In IEEE 802.21 working group researchers are working on Media Independent Handover Services [44]. They are not focusing on one specific access technology, but on handovers and interoperability between different access technologies, including both 802 and non-802 technologies. The 3GPP [1] has concentrated on building the next generation cellular networks, but the road there leads to IP based converging networks as well. The IP Multimedia Subsystem (IMS), which enables standardized IP based service provision via the packet switched domain, was introduced in the 3GPP Release 5. The first practical step toward the converging networks is the commercial Unlicensed Mobile Access (UMA) [106], where both voice and data services can be accessed through the public IP network (using e.g. WLAN access) via the cellular core.

In addition to standardization bodies there exist several projects, which focus on 4th generation network research.

- IST (Information Society Technologies) Moby Dick – Mobility and Differentiated Services in a Future IP Network [25]
- IST Ambient Networks – Mobile and Wireless Systems Beyond 3G [77]
- IST WINNER – Wireless World Initiative New Radio [20]
- IST NOMAD – Integrated Networks for Seamless and Transparent Service Discovery [90]
- WIDE – Widely Integrated Distributed Environment (includes subprojects such as Nautilus6, KAME and USAGI) [28]
- IPonAir – Next Generation Wireless Internet [128]
- ANWIRE – Academic Network on Wireless Internet Research in Europe [32]
- IST BRAIN (Broadband Radio Access for IP-based Networks) and IST MIND (Mobile IP based Network Developments) [121]

1.4 Outline of the dissertation

The rest of this dissertation is organized as follows. Chapter 2 presents several protocols that are proposed for IP mobility management in different protocol layers. We focus in more detail on Mobile IPv6 protocol as well as on some proposed performance enhancements. A particular attention is paid to the Flow-based Fast Handover method for Mobile IPv6 (FFHMIPv6) for shortening the registration phase of Mobile IPv6 and its analysis in different environments.

Chapter 3 presents the problematic related to IP mobility management in the heterogeneous wireless overlay networks. Mobile IPv6 protocol functionality and performance is analyzed from the point of view of several divergent access networks and multiaccess devices. A few problem points are identified and several research works are presented for this purpose. Especially, link layer utilization and interface selection procedures in multi-access context are discussed. VERHO (VERtical HandOvers in 4G System) system is presented as a reference solution for the client controlled mobility management for the converging 4G networks. VERHO utilizes information from different sources and calculates the best interface at a current time resulting in an Always-Best-Connected access for the user and his applications. A few prototype applications for adaptive utilization of the network resources are also presented.

Chapter 4 summarizes the dissertation and points out the main conclusions related to mobility management in wireless networks. Also, future research directions are discussed.

2 IP MOBILITY MANAGEMENT

2.1 Mobility and mobility management

Mobility can be divided into several kinds of mobility, depending mainly on the actor of movement. Movement can be

- Personal – A person moves from one network-connected device to another,
- Node – A node (i.e. mobile terminal) changes its point of attachment to the network. Network mobility is a special case of node mobility,
- Application – A networking application is migrated from one network-connected device to another network-connected device,
- Session – This is related to application mobility. A networking session is moved from one networking device to another or
- Service – Services that are available for a subscriber at one network location are made available at the new location where he/she moves.

All these mobility types set different requirements to the mobility management. In this dissertation we discuss mostly node mobility from the technical perspective.

2.1.1 Handover process

Regardless of the IP mobility management protocol, the process of a handover consists of

1. Link layer movement,
2. IP layer movement detection,
3. IP (re-)configuration,

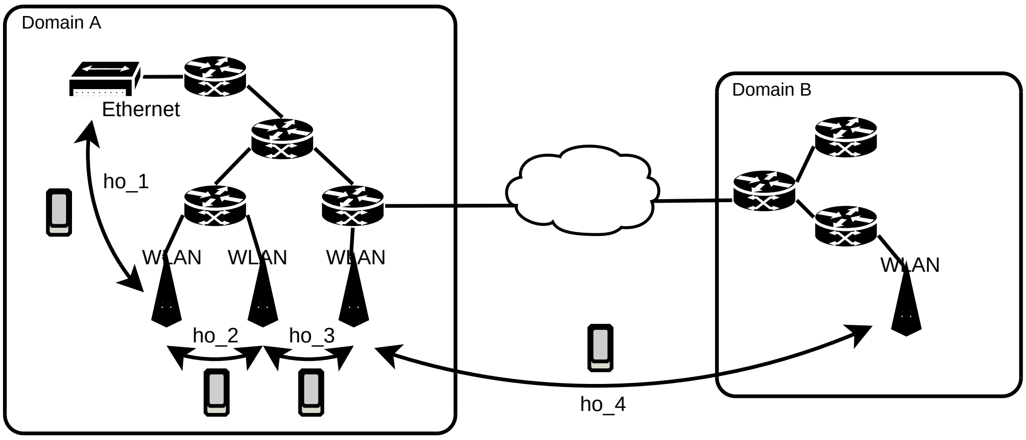

FIGURE 2 Different types of mobility

4. Authentication, Authorization, Accounting (AAA) and
5. Handover management signaling.

First, a Layer 2 Access Point (AP) change is usually handled by the Link Layer itself. There are various access technologies (e.g. IEEE 802.11, cellular networks), and each of them might have its own way of handling the change in APs (or Base Stations, BSs). A change of APs might also result in a change in the IP subnet, which consequently means a change in the mobile node's IP settings.

IP movement detection is meant to determine whether the IP settings of the mobile node are still valid at the new point of attachment or not. If they are, the handover can be considered finished. No IP reconfiguration is needed, thus the handover is invisible both to the IP mobility protocol and application connections disregarding possible small delay and packet loss/retransmissions.

The process of detecting Layer 3 movement is an area that is currently being worked on by the Detecting Network Attachments (DNA) charter at the IETF. For reliability and robustness these solutions try to utilize Layer 2 information (e.g. an event when the link becomes capable of carrying packets) as well as Layer 3 information (Router and Neighbor Discovery of IPv6). In step 3, mobile terminal needs to perform IP reconfiguration, which results in a change in IP settings. Some protocols working in layers above Layer 3 cannot manage the IP settings change. The simplest example is TCP, where the connection in the transport layer is bound to IP addresses at the network layer. Therefore, if the IP address associated to a TCP connection is no longer valid, the TCP connection breaks. This fact is the driving force behind the research for finding ways to handle IP mobility.

AAA (Authentication, Authorization and Accounting) is the process that is needed to access a network from the legal point of view. Currently there is no standard way for AAA that could be generally used when roaming between different wireless IP networks (and domains). Some possible ways of resolving this could be Radius [94] or Diameter [15].

Mobility management consists of handover management and location management [97]. In handover management, the mobility is handled in such a way that during IP subnet handovers the current application connections remain intact, thus ongoing connections will be either preserved or restarted after a movement. Location management means that the terminal also has to inform the current location (current IP address of an interface) to its communication peers or some intermediate router in the network. This way all willing communication nodes can access a moving terminal even if it is moving between subnets. Therefore, location management consists of two tasks:

1. Location update – To track the location of mobile nodes, their location must be registered and this registration must be updated on every change
2. Traffic delivery – Using the location information, traffic is delivered (routed) to the mobile node's current location

As 4th generation networks carry several types of applications with different traffic charasteristics and quality demands. As in handover procedures the IP addresses change due to subnet change, the Quality of Service re-negoatiation might also be necessary. This can be performed before or after the actual handover procedures.

2.1.2 Handover types

Here, we will consider the terminology related to different kinds of handovers, which can be classified in various ways. Handover (or handoff) itself refers to change of Point of Attachment (PoA) to the network. Roaming refers to agreements between separate operators to enable movement of subscribers between operator networks (i.e. administrative handover). Figure 2 presents different types of mobility.

A term macro (i.e. global) mobility refers to mobility over a large area (see Figure 2, ho_4). Usually this includes IP mobility and related address registration procedures, Mobile IP(v6) being one example of this. Micro (i.e. local) mobility covers mobility over a small area, for example within a subnet or a domain.

A multi-interface mobile node is likely to have interfaces of different access technologies, therefore handovers can also be classified whether they happen between that same access technologies or between different ones (e.g. WLAN to GPRS).

- Horizontal (i.e. intra-technology) handover – Handover between the same access technologies (see Figure 2, ho_2)
- Vertical (i.e. inter-technology) handover – Handover between the different access technologies (see Figure 2, ho_1)

Handovers can be also devided into L2 and L3 handovers based on the protocol layers involved in the handover process. In a pure L2 handover the IP settings do not change during the handover, thus only link technology dependent handover procedures are needed (see Figure 2, ho_2). When IP subnet changes due to AP change, also IP reconfiguration is needed (see Figure 2, ho_3). For example Mobile IPv6 can be utilized for the L3 handover.

Hard and soft handover refer to whether the mobile node looses connection to the network during handoff or not, respectively.

- Hard handover – During a hard handover there is a period of time when the mobile node has no connection to the network at all. When making the handover, the node disconnects from its old link and reconnects at the new one. It can happen in a case when the mobile node has e.g. only a single network interface. Usually a node can not be connected to multiple links or Access Points at the same time via the same network interface.

- Soft handover – When the mobile node makes a handover without at any time being completely offline, then we talk about soft handovers. To perform this, it is very likely that multiple network interfaces must be present at the mobile node (depending on the access technology used). [1]

During handover, packet loss is likely to occur and one of the main goals of mobility management protocols is to minimize this packet loss. In make-before-break handover the mobile node knows beforehand that it will soon encounter a hard handover, thus it may perform some steps before breaking the connection at the old link. Otherwise, at the new link the mobile node would need to perform too many steps before it can set up a working IP configuration, which would result in long delays and significant packet loss. The latter kind of handover is called break-before-make. The aim is to provide seamless handover, where upper layers (e.g. applications) experience minimal disruption.

Also, based on the handover control, the handover can be divided into different groups [59].

- Mobile-initiated handover – The MN is the one that makes the initial decision to initiate the handover.

- Network-initiated handover – The network makes the initial decision to initiate the handover.

- Mobile-controlled handover – The MN has the primary control over the handover process.

- Network-controlled handover – The network has the primary control over the handover process.

- Mobile-assisted handover – Information and measurement from the MN are used by the core network to decide on the execution of a handover.

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[1] UMTS technology provides also soft and softer handovers with one single interface.

- Network-assisted handover – A handover where the core network collects information that can be used by the MN in a handover decision.

In this dissertation we consider mainly mobile initiated and mobile controlled handovers.

Based on architectural principles, the mobility management can be divided into tightly and loosely coupled systems. In the tightly coupled integration, the unlicensed access networks appear to the cellular core network as another cellular access network, thus the multi-access system is built using the existing cellular core network (e.g. Unlicensed Mobile Access, UMA) [106]. In the loosely-coupled integration, the unlicensed access networks and cellular networks are functioning as accesses to the IP network and the mobility management is handled with IP layer mobility management protocol. The 4G networks, as well as this dissertation, focus on the loosely coupled mobility management.

Mobility related terminology with e.g. mobile network entities, handover types and handover procedures are presented in [59].

2.1.3 IP mobility management protocols

Mobility can be handled at different layers of the OSI protocol stack [97], [37], [2]. Table 1 shows different layers of the TCP/IP model, where mobility may be considered, and their comparisons made between them. Note that the overlay protocol layer is a shim layer between the network and transport layers, and thus not an actual part of the TCP/IP reference model. Link layer mobility management provides only link layer mobility, thus it does not provide movement in the IP networks.

Network layer seem to be the most preferred layer of handling IP mobility. Basically, there is one IP address acting as an identifier and another as a locator, Mobile IPv4 [88] and Mobile IPv6 [46] being two examples. Mobile IP is seen as the most likely choice for the mobility management in All-IP networks. Overlay network refers to a new layer between the network and transport layer. This means it is quite easy make changes and additions to the protocol, while the large-scale deployment can be difficult. As an example of these Internet Indirection Infrastructure I^3 [103] and Host Identity Protocol (HIP) [73] may be pointed out.

Transport layer solutions usually try to enhance transport layer functionality in the wireless lossy environment. Some of these are just enhancements to the current protocols, such as Indirect TCP [7], and some are newly designed protocols such as Stream Control Transmission Protocol (SCTP) [123] and its mobile enhancement mSCTP [52]. There are several transport layer protocols for different purposes, thus there are different applications for them also. For example, if the mobility is handled in the transport layer, the mobility management applies only to applications using the protocol in question. This would result in a need for several mobility management protocols.

By application layer mobility it is meant that the application itself handles the mobility, usually by just re-establishing all the connections. Also, Session Ini-

TABLE 1 Mobility management in Different Layers

Layer	Benefits	Disadvantages
Application	Easy and requires modifications only to the application itself.	Duplicated code in separate applications. A needy application may not get mobility support.
Transport	May cure weaknesses of a transport protocol caused by changing link conditions.	Applies only to applicationss using a specific transport protocol.
Overlay	In an overlay network it is easy to add extra functionality and to solve otherwise hard problems. Identifier and locator splitting is usually a consequence.	Deployment may be problematic, although it depends on the overlay design. The overlay introduces extra overhead for routing traffic.
Network	Applies to all upper layer protocols and applications. IP is the dominant network protocol, so only IP may be modified.	Unaware upper layer code may behave oddly. For example, transport layer congestion control algorithms may see congestion when there is none.
Link	Well separated from upper layers. Medium Access Control (MAC) addresses rarely change. Not really affected by IP changes. Link layer and upper layer mobility are considered as separate domains.	Does not handle IP mobility.

tiation Protocol (SIP) [95] is often mentioned as an application layer solution for connection establishments and includes mobility management features as well.

In this dissertation only Mobile IPv6 protocol is considered, because it is thought of being the most likely solution for future mobility management. For more information on other mobility protocols and their comparison can be found from [2], [97], [37] and [29].

2.2 Mobile IPv6 protocol and handover

Mobility support in IPv6 [46] enables transparent routing of packets to the Mobile Node. In a home network, MN is assigned a permanent home address (HoA), which is used in every application layer connection. When MN changes its IP layer attachment in the network, it acquires a new local address from the foreign

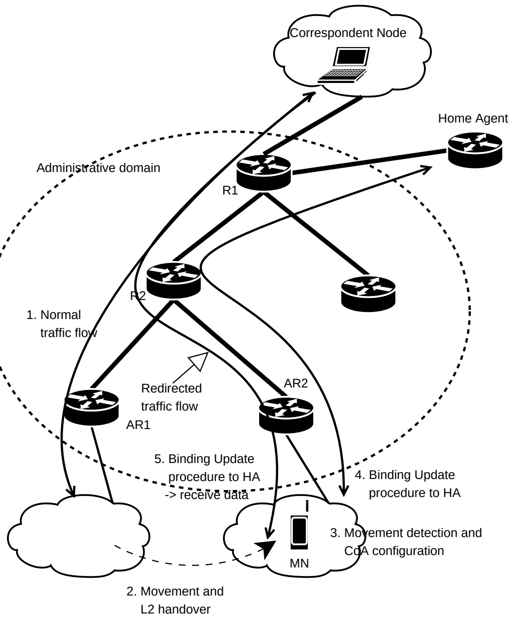


FIGURE 3 Mobile IPv6 functionality

network to becoming again accessible. This address, called the *Care-of-Address* (CoA), is registered through a *binding update* (BU) process to a special router in the home network called the *Home Agent* (HA). Thus the HoA is used as an identifier and the CoA as a locator. The HA maintains a binding cache, in which the HoA-CoA bindings are stored, and employs tunneling to redirect the flows to the current CoA of the MN. In the basic mode, MN communicates through a two-way tunnel via the HA with the Corresponding Nodes (CNs). Mobile IPv6 functionality is presented in Figure 3.

Mobile IPv6 handover procedures consist of three parts. First the MN performs the link layer handover dependent of the access technology. Link layer handover processes and performance is out of scope of this dissertation, for more information on link layer handover procedures, refer to the specification of any specific technology, or for performance results in case of IEEE 802.11 refer to [64] or [109].

After a link layer handover the MN needs to detect if it has changed the IP subnet. This is performed by listening to periodical Router Advertisements (RAs) sent by Access Routers or by Neighbor Unreachability Detection (NUD) [74]. MIPv6 specification [46] defines that the RA interval should be a random value between 0.05 and 3.0 seconds, thus the average RA waiting delay would be about 1.5 seconds. MN can also request the RA by sending a Router Solicitation message, in which case the movement detection would be about a Round Trip Time (RTT) to the Access Router (AR) plus the random solicitated RA delay (0 - 0.5s) in the AR.

After movement detection, the MN has to acquire a new CoA to be again reachable. For this MN can utilize either stateless or stateful address autoconfiguration defined in [105] and [23], respectively. In the former alternative the CoA is calculated from the RA message, which includes the subnet prefix and the MAC address of the interface in question. In the latter case, the address is requested from a DHCPv6 server. The former would be preferred due to lack of network support. The newly generated address needs to be verified for uniqueness via Duplicate Address Detection (DAD). DAD takes about 1.0 seconds due to the included waiting period.

Finally, the CoA needs to be registered to the HA with a Binding Update process, so that the HA knows the current location of the MN. This takes about the round-trip delay to HA, if the HA is not performing the DAD. The MN can also decide to register its CoA to the Corresponding Nodes (CNs) (i.e. the nodes it is communicating with) in which case also the CNs maintain a binding cache. As a security procedure the Return Routability needs to be done before the BU procedure to the CNs. This induces about two times the round-trip delay to the CNs.

The most significant enhancement in MIPv6, compared to the mobility support in IPv4, is *Route Optimization* (RO) which means that the MN can also send BUs to the nodes it is communicating with. These corresponding nodes (CNs) also maintain a binding cache. Thus CNs can send packets directly to the MN without two-way tunneling via HA, therefore improving the End-to-End communication delay. This happens at the expense of the handover delay, which is increased by about two round-trip times following from sending BUs to CNs and the Return Routability (RR) procedure. For details of Mobile IPv6 functionality, required data structures and header formats, refer to [46].

Although MIPv6 enables mobility at the IP layer, the processes related to MIPv6 handover procedures described earlier (i.e movement detection, CoA configuration, CoA registration) result in a period of time when the MN cannot receive or send any packets. This period of time is called the *handover delay* or *handoff latency*. Even small disruptions affect both real-time and download type applications (e.g. with VoIP traffic the maximum delay would be about 200 ms). Next, we present the essential Mobile IPv6 handover delay results published within the last few years.

Mobile IPv6 process and especially handover functionality are presented in the 6NET deliverable in [24]. Each handover component of Mobile IPv6 is analyzed theoretically based on the Mobile IPv6 specification [46]. MIPv6 handover delay is also analyzed in a Mobile IPv6 for Linux (MIPL) environment. Handover delay is dependent on the RA interval being about 2-3 seconds. With solicited RAs the delay is about 2 seconds. Also, the Fast Handovers for Mobile IPv6 [54] is presented and its handover delay is analyzed theoretically.

Similar analysis about the theoretical Mobile IPv6 handover delay on a component basis is presented in [113]. Ways of enhancing the Mobile IPv6 handover, e.g. the effect of RA interval, cross-layer interactions, and router support are presented. The author claims that the Mobile IPv6 handover processes need some enhancements for better support for seamless operation for applications. The theoretical analysis is rather extensive. However, no practical tests were performed to support the claim.

2.3 Mobile IPv6 enhancements

Numerous enhancements for MIPv6 have been proposed in the research community. All of them improve one or more of the MIPv6 handover phases presented in Section 2.2. Most of the enhancements can be divided into the following types based on the operational principle.

- Speeding up IPv6 features – The IPv6 router discovery as well as DAD may be speeded up in several ways. For example in *Fast Router Advertisements* a number of solicited RAs may be sent immediately without any random delay in AR [19]. In *Optimistic DAD* [72], the DAD may be left performed due to the improbability of duplicated address with stateless address autoconfiguration.

- Anticipation – Movement detection delay can be reduced by anticipating the shortly occurring handover by link layer support and thus performing some (for example CoA configuration) of the handover processes before the actual handover. Positioning information can also be utilized for the trigger creation.

- Local Home Agent – The HA might be located quite far geographically, which increases the CoA registration delays. If a HA is placed on each IP domain, then one HA would always be quite near, again decreasing the registration delay. Hierarchical MIPv6 [100] discussed in the next subsection operates according to this principle.

- Tunneling – During handovers the traffic heading for old location (old CoA) is tunneled to the current location. For this the old Access Router is most probably utilized, as in Fast Handovers for MIPv6 [54].

- Multicasting and routing – MN anticipates the handover and along with creating a new CoA it joins a Multicast group with the new CoA. Thus the flows are routed to the old and new location of the MN, see for example [112].

- Buffering – Together with anticipation and tunneling buffering at the new AR can be utilized before the MN comes accessible at the new Point of Attachment, see for example [81].

Presenting all the numerous Mobile IPv6 extensions proposed is out of scope of this dissertation. Instead, we present only the most profound methods specified in the IETF MIPv6 Signaling and Handoff Optimization (mipshop) Charter [63], Hierarchical Mobile IPv6 [100] and Fast Handovers for Mobile IPv6 [54].

2.3.1 Hierarchical Mobile IPv6

The *Hierarchical Mobile IPv6* (HMIPv6) [100] reduces the registration time of a new CoA and signaling load by introducing a new node called the *mobility anchor point* (MAP). HMIPv6 handles the local and global mobility in a different way. Mobility management inside the local domain is handled by the MAP, and between separate MAP domains by the HA, as in MIPv6. MAP acts basically as a local HA in foreign network tunneling flows to the current location of the MN.

Local mobility is handled with two CoAs: *regional CoA* (RCoA) and *on-link CoA* (LCoA). When MN moves to an entirely new MAP domain, it receives or forms a new RCoA, which is registered to the MAP and HA (and possibly to CNs). Now, traffic is going a route CN->HA->MAP->RCoA. When MN changes its point of attachment inside the MAP domain, it only needs to inform the MAP about the new on-link CoA, which matches to the current IP subnet prefix. MAP intercepts the packets heading for the RCoA and tunnels them to the new LCoA acting just like HA.

The HMIPv6 minimizes the amount of signaling to CNs and to the HA. Also, the CoA registration delay is reduced. However, HMIPv6 might experience some scalability problems if MAP has to handle too many MNs [69]. Also, MAP introduces more complexity and is a possible point of failure in the network. Without Route Optimization in the foreign MAP domain, the traffic flows are doubly tunneled (both HA and MAP create tunnels) increasing the header overhead. The MAP is likely to be at the ingress/egress point of the (sub)network which means that the registration delay might still be too large for delay critical applications. For more information on the functionality details, refer to [100].

2.3.2 Fast Handovers for Mobile IPv6

The *Fast Handovers for Mobile IPv6* (FMIPv6) [54] shortens the delay caused by the CoA acquiring phase and employs tunneling to reduce packet loss during the handover.

When MN receives information about the next point of attachment, it sends a *Router Solicitation for Proxy* (RtSolPr) message to the Previous AR (PAR) to start the fast handover procedure. With the information provided in the Proxy Router Advertisement (PrRtAdv) message, MN formulates a prospective new CoA and sends a Fast Binding Update (FBU) message. The purpose of FBU is to authorize oAR to bind previous CoA to new CoA, so that arriving packets can be tunneled to the new location of the MN. FMIPv6 describes two modes of operation, *predictive* and *reactive*. In predictive mode MN sends FBU to the PAR and receives Fast Binding Acknowledgement (FBACK) from the PAR while connected to the previous link. Whereas, in the reactive mode this message exchange is done via the New Access Router's (NAR) link.

According to several publications FMIPv6 has shown promising results. However, it is dependent on link layer scanning procedures and some "guessing" to anticipate the next PoA. Also, the fast handover procedure induces network support for both generation of the new CoA (possibly Candidate Access Router Discovery (CARD) protocol [57]) and tunneling.

A combination of the HMIPv6 (see section 1.1) and FMIPv6 called Fast Handovers for Hierarchical Mobile IPv6 (F-HMIPv6) has also been proposed in [48]. In F-HMIPv6 the entity performing the functionality of FMIPv6 is the MAP instead of the PAR. However, the F-HMIPv6 still shares the disadvantages of HMIPv6 and FMIPv6.

2.3.3 HMIPv6 and FMIPv6 performance

Several simulative analyses (with a ns-2 simulator) for comparing HMIPv6 and FMIPv6 with Mobile IPv6 have been published.

According to [47] the handover delay of FMIPv6 is about 20 ms while for Mobile IPv6 it is about 60 ms. The authors use hierarchical network topology with 9 IEEE 802.11 BSs and UDP based Constant Bit Rate (CBR) traffic. However, the numeric values are not that meaningful due to the fact that the simulative environments tend to be a little simplified and do not include all the variables as would be the case in real environment. Also, the handover delay is dependent on the network topology. But relative results can still be obtained, as the handover delay of FMIPv6 is about one third of Mobile IPv6. When the wireless channel becomes congested due to increased amount of MNs in the coverage, increase in signaling messages in FMIPv6 increases the handover latency significantly compared with MIPv6.

The HMIPv6, FMIPv6, and F-HMIPv6 methods are compared to Mobile IPv6 with TCP based traffic in [38]. It is shown that FMIPv6 mechanism alone is capable of reducing the handoff latency 15-fold when compared to the standard MIPv6. The hierarchical structure is also capable of reducing the handoff latency by 7 times compared with the MlPv6. With a combined FMIPv6 and HMIPv6, the overall handoff latency is reduced by 18 times compared with the standard MIPv6. Since then the authors have proposed A Seamless Handoff Architecture for Mobile IP (S-MIP) [39], which should provide truly seamless handovers.

Similar performance comparison of MIPv6, HMIPv6, FMIPv6 and F-HMIPv6 as in [47] has been presented in [87]. The results are also quite similar. In general the F-HMIPv6 provides the smallest handover delay, followed by FMIPv6, HMIPv6 and finally the standard MIPv6. But in scenarios where the users produce a low rate with small packets (e.g. VoIP) the basic Mobile IPv6 can function with better performance due to smaller signaling overhead. Also, in saturating radio conditions (i.e. congestion) the basic Mobile IPv6 is found to be more effective for the same reason.

The Mobile IPv6 handover is compared with the two operation modes of FMIPv6 with IEEE 802.11 access network in [70]. FMIPv6 is found to offer smaller handover delay, even if in optimal cases the MIPv6 handover delay is quite close to the FMIPv6.

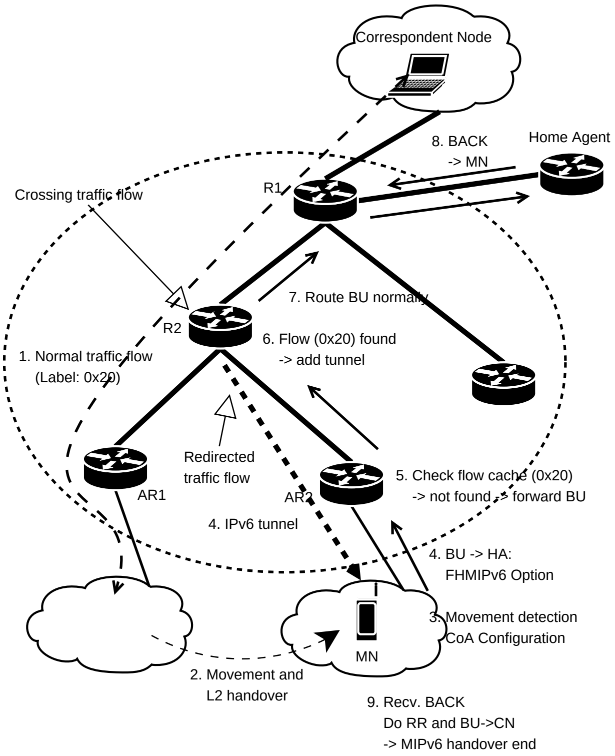


FIGURE 4 FFHMIPv6 functionality

2.4 Flow-based Fast Handover for Mobile IPv6

In this section we propose a Flow-based Fast Handover mechanism for reducing the CoA registration delay.

2.4.1 Basic functionality

FFHMIPv6 is a link layer independent, interoperable and fully backward compatible enhancement for MIPv6. It uses flow state information (i.e. flow cache) in the routers and IPv6-in-IPv6 tunneling to enable reception of flows during the BU process.

The FFHMIPv6 functionality is shown in Figure 4. When it detects that it has moved to a new IP subnet, it configures a new CoA (Figure 4, phases 2 and 3) and starts to register it to the HA via the BU process (Figure 4, phase 4). In the FFHMIPv6 method a *Hop-by-Hop* header, including the old CoA and the addresses of the CNs, is added to the BU register message heading for the HA. The resulting BU message is called the Flow-based Fast Handover BU (FFHBU) to separate it from the basic BU message. The goal of this BU message is to redirect all the MN's flows to the new location (i.e. new CoA).

Every IPv6 capable router is required to maintain a flow cache of the active flows it routes. In every router between the MN and the HA (on the BU path), the flow cache of the router is compared with the flow information found from the Hop-by-Hop header of the BU (Figure 4, phase 5). If the traffic flow is found, an IPv6 tunnel is established between the router in question and the new CoA of the MN, and the traffic flow is redirected to the established tunnel (Figure 4, phase 6). At this phase the MN using FFHMIPv6 is able to receive the data. We call this router the Crossover Router (CR).

Next, the address of the CN in question is erased from the Hop-by-Hop frame, so that the FFHMIPv6 process is not performed again in another router for the same flow. Finally, the BU message is forwarded towards the HA, and at the next hop the same procedure is repeated (Figure 4, phase 7). Based on the basic Mobile IPv6 functionality, MN has to wait for the Binding Acknowledgment (BACK) from HA to be able to send or receive data. Also, in the case of Route Optimization, MN would need to perform Return Routability as well as the BU process to the CN to be able to redirect the CN's flows to the new location (Figure 4, phase 9). During the tunneling (lifetime e.g. 3 seconds), MN has time to register the new CoA to the HA and CN(s), thus the FFHMIPv6 enables reception of the traffic flow simultaneously with the BU process therefore minimizing *downstream* packet loss. For more on basic FFHMIPv6 downstream functionality, refer to publications [PI], [PIII] and [PIV].

2.4.2 Upstream enhancement

According to MIPv6 specification [46] the *upstream* traffic is possible only after a BACK message has been received from the HA. We specify a new type of address called Hand-of-Address (HofA), which can be used during the BU process to the HA. The MN receives a temporal and unique HofA from the new IP subnet from the new AR, after requesting it with the BU message. The ARs have a range of their subnet addresses which cannot be used as CoAs, but are reserved for handover purposes. Now, the MN can tunnel the upstream packets from the HofA to the AR (old CoA→CN encapsulated to HofA→new AR) enabling it to pass ingress filtering of the AR. This way the upstream traffic is enabled before the BACK from the HA. A flow chart of the FFHMIPv6 functionality with upstream enhancements is shown in Figure 5.

In publication [PVII] we have discussed different implementation suggestions on

- the amount and scope of HofA addresses
- HofA assignment procedure (used without signaling, assigned on request)
- FFHMIPv6 upstream message passing between MN and AR

2.4.3 Theoretical analysis

Theoretical analysis provides information about the likely performance of the considered methods. The BU signaling delays have been calculated with the MIPv6, HMIPv6, FMIPv6, and FFHMIPv6 handover methods.

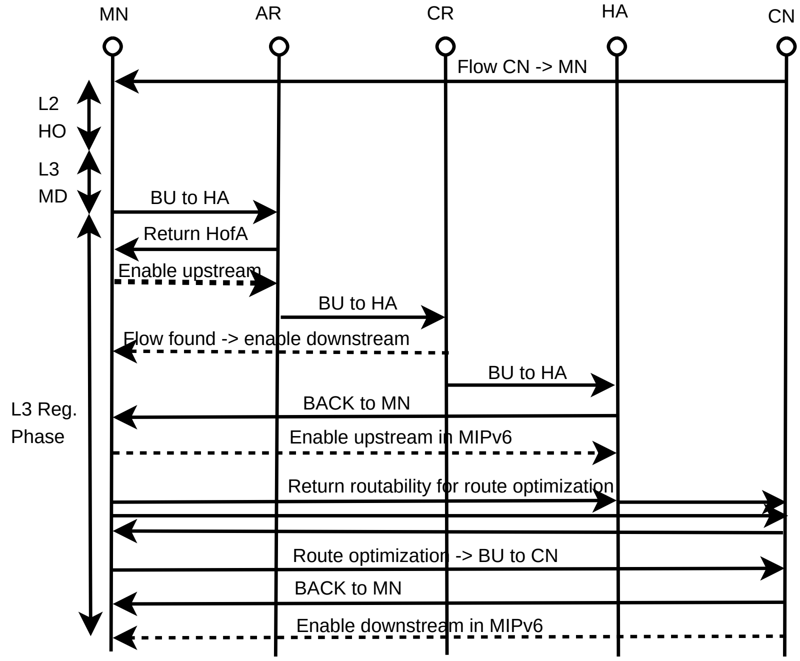


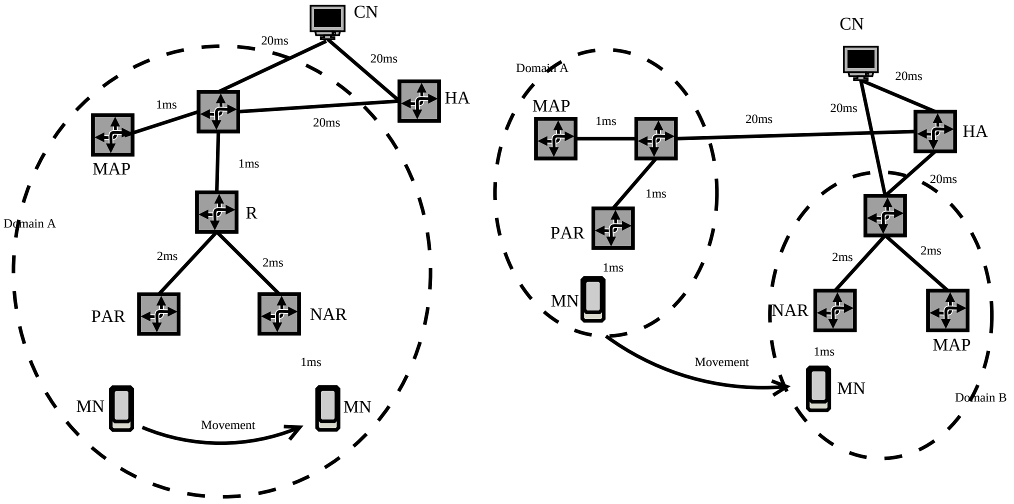
FIGURE 5 FFHMIPv6 with upstream enhancements

Two sample scenarios here represent the handover situation in the best (1) and the worst (2) case for the FFHMIPv6 method (see Figure 6). In scenario 1 the MN changes the access router within the same MAP domain (MAP exists only in HMIPv6 network), and the access routers (PAR and NAR) are connected to the same router (the cross-over router in FFHMIPv6). In scenario 2, the MN changes its MAP domain when considered from the perspective of the HMIPv6 method, while a cross-over router for the FFHMIPv6 does not exist.

The handover delay is defined to be the time from the moment when MN sends a BU message toward the HA to the moment when the MN receives the first packet via the new AR. Of course, the overall handover also consists of several other components such as a link layer handover, IP layer movement detection and CoA configuration. But the FFHMIPv6 method optimizes only the CoA registration phase of the handover process. Other phases of the handover delay are out of scope of this particular research.

We concentrate on a situation, where the MN cannot anticipate the shortly occurring handover (e.g. with L2 triggers, signal strength, positioning system, etc.). This assumption has an effect on the performance of the FMIPv6 method, which functions in the reactive mode, thus the MN sends the Fast Neighbor Advertisement (FNA) message including the FBU to the NAR after the link layer handover.

Route optimization is not used in this theoretical analysis, so all the flows from CNs are routed via the HA. The FFHMIPv6 method is therefore used to redirect the flow from the HA to the new CoA, and the handover delay consists of the BU process to the HA. There are also other factors that might affect the



a) Scenario 1 (best)

b) Scenario 2 (worst)

FIGURE 6 The theoretical analysis scenarios

TABLE 2 The theoretical analysis in the best (1) scenario

Method	Procedure / delay calculation
FFHMIPv6	$MN : BU \rightarrow CR$ $2 * (1ms + 2ms) = 6ms$
HMIPv6	$MN : BU \rightarrow MAP$ $2 * (1ms + 2ms + 1ms + 1ms) = 10ms$
MIPv6	$MN : BU \rightarrow HA$ $2 * (1ms + 2ms + 1ms + 20ms) = 48ms$
FMIPv6	$MN : FNA \rightarrow NAR, NAR : FBU \rightarrow PAR, PAR : FBACK \rightarrow NAR$ $2 * (1ms + 2ms + 2ms) = 10ms$

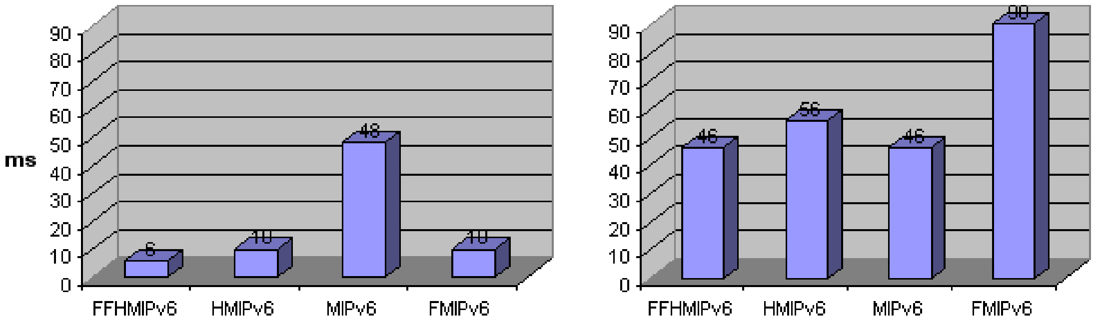
overall BU process delay, such as the processing delay in routers inflicted by the Hop-by-Hop header and the flow state information procedures. These factors are not taken into account in this analysis.

The link delays have been selected to represent networks where access routers are near, but the HA and CNs can be located quite far away. The link delays have been presented in Figure 6 varying between 1ms - 20ms. The downstream handover delay calculations are presented in both the best and worst case scenarios in Tables 2 and 3, respectively.

Figure 7 presents the results of the theoretical analysis. In scenario 1, with FFHMIPv6 handover method the MN is able to receive the flow after the BU message to the crossover router. HMIPv6 is almost as effective as FFHMIPv6, because within the same domain it requires only the BU message to the MAP. MIPv6 requires the BU process to the distant HA. Also, if the Route Optimization would be used, the signaling benefits in the best scenario would be even emphasized, if compared to MIPv6. In scenario 2, with FFHMIPv6 the crossover router

TABLE 3 The theoretical analysis in the worst (2) scenario

Method	Procedure / delay calculation
FFHMIPv6	$MN : BU \rightarrow HA$ $2 * (1ms + 2ms + 20ms) = 46ms$
HMIPv6	$MN : BU \rightarrow MAP, BU \rightarrow HA$ $2 * (1ms + 2ms + 2ms) + 2 * (1ms + 2ms + 20ms) = 56ms$
MIPv6	$MN : BU \rightarrow HA$ $2 * (1ms + 2ms + 20ms) = 46ms$
FMIPv6	$MN : FNA \rightarrow NAR, NAR : FBU \rightarrow PAR, PAR : FBACK \rightarrow NAR$ $2 * (1ms + 2ms + 20ms + 20ms + 1ms) = 90ms$



a) Scenario 1 (best) b) Scenario 2 (worst)

FIGURE 7 Theoretical analysis results in the (a) best and (b) worst case scenarios

is not found, so the FFHMIPv6 method is practically functioning as effectively as MIPv6, thus BU process to the HA is required. With HMIPv6 the MN must perform the BU process to the new MAP and HA, because MN changes the network domain. In a reactive mode of FMIPv6, signaling to the PAR is needed to establish a tunnel between the PAR and new CoA. This increases the BU delay in the worst scenario to the extent where the usage of FMIPv6 is not sensible anymore. In the best scenario the packets can be redirected quite fast.

The upstream handover delay of the FFHMIPv6 with upstream enhancements is always small, because the new AR is always found close. Even if the HA and the CN(s) are at a large distance, with the HofA the upstream traffic will undergo only a minor delay during the new CoA configuration time, depending only on the RTT to the new AR versus the actual RTT to HA for the basic MIPv6 or to MAP for the HMIPv6. Thus, the delay in upstream traffic is practically constant and always smaller than with MIPv6 or HMIPv6 (unless the new AR is the HA or the MAP). A theoretical comparison of the upstream handover with the two scenarios (see Figure 6) is presented in Figure 8. As the calculation process is similar as in the theoretical downstream analysis, the process is not presented here anymore.

In scenario 1 with Fast Upstream of FFHMIPv6 the MN is able to transmit after the BU message has reached NAR and it has returned a HofA. HMIPv6 re-

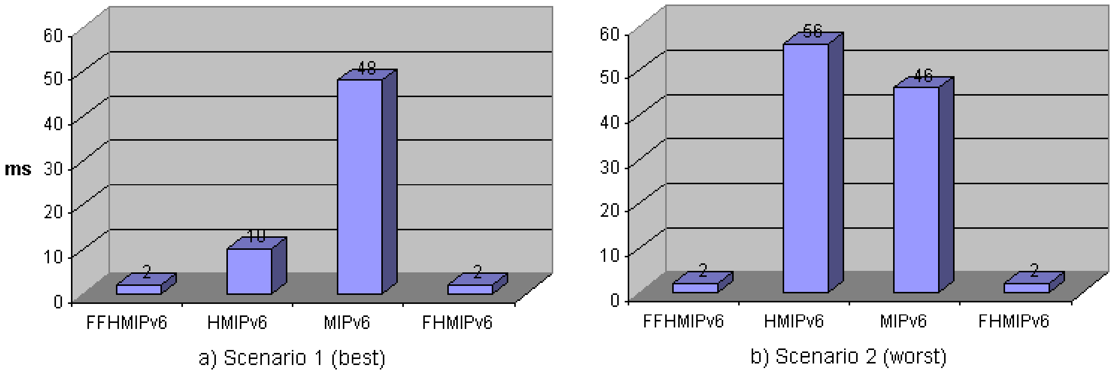


FIGURE 8 Theoretical analysis of upstream handover in the (a) best and (b) worst case scenarios

quires that the BU message is acknowledged by the MAP with a BACK message. MIPv6 requires that the BU message is acknowledged by the distant HA. FMIPv6 can send upstream data as fast as with the HofA if the MN has been able to formulate a prospective new CoA by PrRtAdv as answer to RtSolPr. In FMIPv6 MN sends FNA to the NAR, but [54] does not actually specify when MN can transmit data after the FNA message. The AR checks the new CoA included in the FNA and if the new CoA is in use AR sends a RA with Neighbor Advertisement Acknowledgment (NAACK). However, in [54] NAACK is only specified to inform if the new CoA is invalid or the Link Layer Address is not recognized, but it is not used to inform of successful new CoA formulation. Thus, in the analysis we have assumed that MN waits for a certain time for the possible RA with NAACK before it begins transmitting. This time was chosen as the time it would take for the AR to immediately respond to the FNA (e.g. the total upstream delay for the FMIPv6 is assumed to be the RTT to the NAR). However, in the case of "reactive" Fast Handover (i.e. the handover instant cannot be predicted) the data packets are tunneled via PAR consuming unnecessary resources of the network. Also, FMIPv6 increases complexity and signaling load of the network as it requires that ARs keep track of the states of their neighbors.

In scenario 2, FFHMIPv6 with HofA, MIPv6 and FMIPv6 function as in Scenario 1 (the route to the HA in case of MIPv6 is slightly shorter). As the MAP domain changes in HMIPv6, the MN sends the BU message to the new MAP, waits for a BACK and then sends a BU to the HA. The MN can transmit data only after the HA has acknowledged the BU, which makes HMIPv6 the worst method in this scenario. For more details on the FFHMIPv6 theoretical analysis, refer to publications [PI], [PII] and [PVIII].

2.4.4 Simulative analysis

The theoretical analysis results are here verified by Network Simulator 2 [80] simulations. In downstream simulations we have used the ns-2 version 2.1b6 and in upstream simulations the ns-2.27, both with the Mobiwan Mobile IPv6 exten-

TABLE 4 The simulation results of the best and worst case scenarios

	Scenario 1		Scenario 2	
	MIPv6	FFHMIPv6	MIPv6	FFHMIPv6
Delay (ms)	58.8	13.8	65.2	65.2
Loss (pkts)	5	1	6	6

sions. The simulations required implementations of the HMIPv6, FFHMIPv6 and Fast Upstream and some necessary changes to the ns-2 and Mobiwan [27]. For details on the required implementations, refer to publication [PVII].

The Best and Worst Case Scenarios

First, in the same network scenarios (see Figure 6) the idea of best and worst situations is simulated in a manner similar to that in theoretical analysis is simulated. Thus, the link delays are the same and the route optimization is not used. MN uses IEEE 802.11b wireless LAN access network, i.e. every AR has a WLAN BS attached to it. The purpose is to verify the theoretical results with simulative results in the two scenarios. However, only FFHMIPv6 downstream has been simulated in the best and worst case scenarios, whereas the theoretical analysis was performed also with FFHMIPv6 upstream.

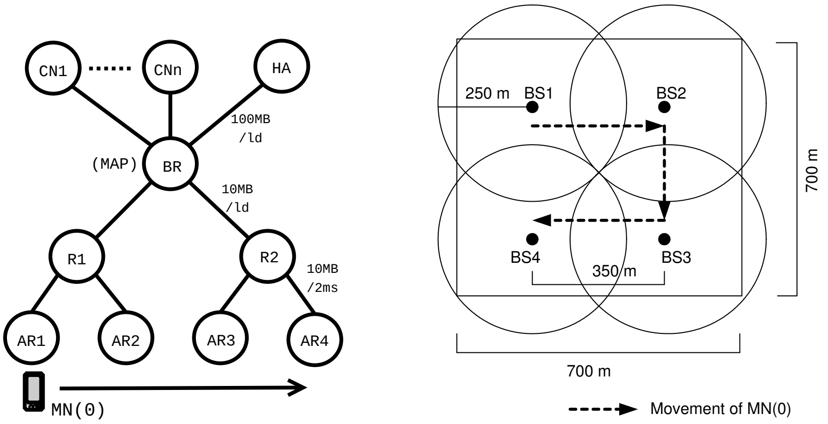
During the handover CN sends UDP-based constant bit rate (CBR) traffic to the MN. Because route optimization is not used, the flow is routed via HA. The packet size of CBR traffic is 500 bytes, and packet sending interval is 0.05 seconds (i.e. 10 kbps). The MN, originally situated in the PAR area, moves at a constant speed of 15 m/s towards the NAR and performs the L3 handover (see Figure 6). The handover delay and resulting packet loss is calculated both with the MIPv6 and FFHMIPv6 handover methods. Handover delay is specified to be from the BU message to the first packet received via the new AR, and packet loss is specified as the number of packets lost during the handover delay.

The results are presented in Table 4. In scenario 1, the FFHMIPv6 handover time is much shorter than in MIPv6, because MN can receive the flow after the crossover router (router *R* in Figure 6a.) has created the tunnel. The packet loss is also self-explanatory, because the MN receives constant bit rate traffic sent at the intervals of 10 ms. In scenario 2, the FFHMIPv6 is functioning as effectively as MIPv6, because a crossover router is not found. The results with MIPv6 and FFHMIPv6 achieved by the ns-2 simulations are similar to theoretical analysis. For more details on the best and worst case simulations, refer to publication [PII].

The effect of CN distance

In these simulations we study the dependency of the distance of the CNs to the handover delay. The distance is simulated by varying the link transmission delays, as in publication [PIII].

The simulation scenario with all of the participating entities and links is shown in Figure 9(a). The scenario consists of four 2Mbps Wireless LAN 802.11 BSs. All BSs are connected to a different AR, representing different IP subnets. Thus also L3 handovers, in addition to L2 handovers, are necessary. The BSs are connected via two routers (R1 and R2) and duplex links to the Border Router (BR), which acts as a gateway point to the external network. The Border Router also functions as the Mobility Anchor Point (MAP) for the Hierarchical MIPv6 handover method. The HA and the CNs are located in the external network.



(a) Topology

(b) BS positions

FIGURE 9 Hierarchical simulation scenario

Figure 9(b) shows the horizontal positions of the BSs. The movement area is 700x700 meters and the BSs cover the entire area. The coverage area of the BSs with omni-directional antennas is about 500 meters in diameter (i.e. radius is 250 m) and the minimum distance between the BSs is 350 m.

The MIPv6, HMIPv6 and FFHMIPv6 handover methods are studied with UDP-based constant bit rate (CBR) traffic. There are 10 MNs moving in the coverage area of the four BSs. Every MN communicates with a corresponding CN. Half of the MNs send UDP based CBR traffic to the corresponding CN and the other half receive CBR. The data rate of every CBR flow is 80 kbps (i.e. packet size 1000 bytes, interval 0.1s).

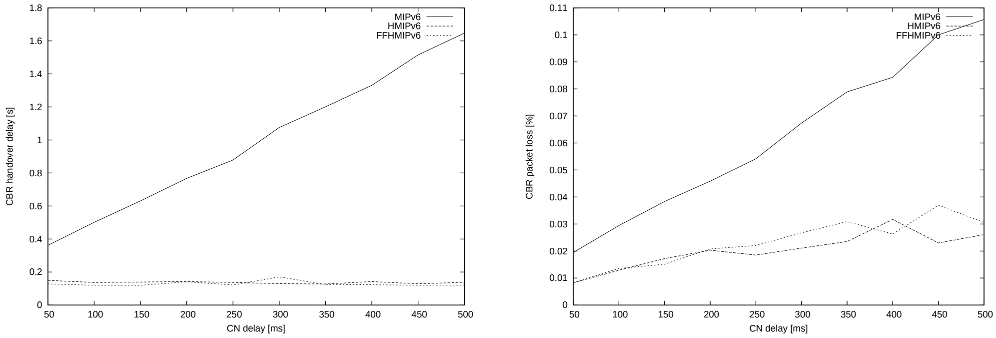
We concentrate on the handover performance experienced by the CBR application of one specific MN (i.e. MN(0)). This MN is moving with a deterministic path with a speed of 10 m/s starting from the BS1 area and moving through all BS coverage areas ending up near BS4. The rest of the MNs (i.e. MN(1) - MN(9)) start from random positions and move randomly according to the random waypoint mobility model provided by ns-2. Route optimization is used in every connection between MNs and CNs.

One iteration period of simulation is 70 seconds and starts with a 20 second warm-up period, where MNs are brought up and the CBR flows begin. After that, the MN(0) starts to move and performs three L3 handovers in one simulation iteration.

To simulate the effect of the distance of the CNs, the link delays (ld in Figure 9) of the CNs are varied between 50 to 500 ms with steps of 50 ms. The same delay is also set between the BR and HA. Every step is iterated 200 times with different random variables (MNs' starting points and movement). The link delay between routers R1-BR and R2-BR is 10ms. In this experiment the handover delay is determined to be the time between the last packet received via the old BS and the first packet via the new BS. The packet loss is the overall loss percent during the simulation.

Figure 10 shows the handover delay and the packet loss as a function of the CN delay. The handover delay with MIPv6 grows linearly when the distance of the CN increases, because the handover time is directly proportional to the distance. The same effect occurs (delay increases linearly) also when the distance of the HA is increased, because the RTT increases accordingly. With HMIPv6 and FFHMIPv6 the handover delay remains quite constant in about 0.1-0.2 seconds. This is quite understandable, because in the FFHMIPv6 the crossover router (R1, R2 or BR) and in HMIPv6 the MAP are always found nearby, regardless of the CN delay.

The packet loss that occurs is not fully accordant with the handover delays. Intuitively, because of CBR traffic, the packet loss curves should follow the shape of the handover delay curves. This difference stems from the fact that the packet loss is defined to be the overall packet loss during the entire simulation. So packets are lost also for reasons other than handovers, such as routers' buffer overflow.



(a) Handover delay

(b) Packet loss

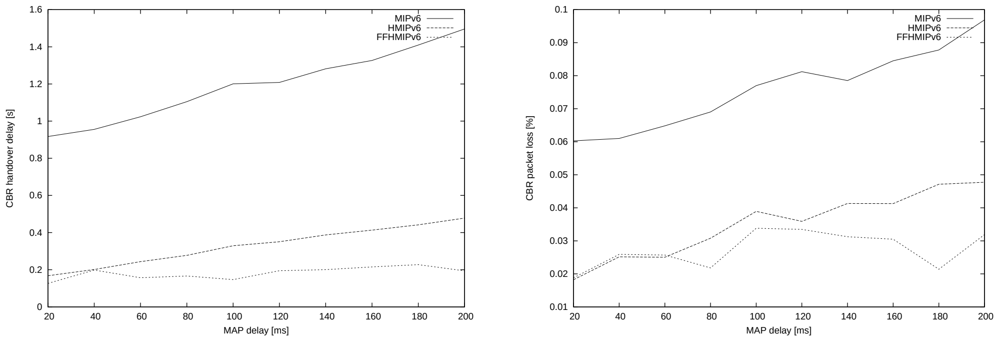
FIGURE 10 Handover performance as a function of CN delay

The effect of MAP distance

According to the HMIPv6 [57] the MAP is generally chosen to be the ingress/egress point of the network (i.e. at the network boundary), so the distance between the MN and the MAP can be quite long. The link delays between routers R1-BR and

R2-BR are varied between 20 - 200ms with 20ms steps to simulate the distance of the MAP. Otherwise the simulation scenario, with the iteration and handover amounts, is the same as in the CN distance simulations (see Figure 9).

The simulation results concerning handover delay and packet loss are presented in Figure 11. Because networks are built hierarchically, the crossover router is usually found closer than the MAP. The results show that the FFHMIPv6 method performs more efficiently than the HMIPv6 method. For details on the distance based simulative analysis, refer to publication [PIII].



(a) Handover delay (b) Packet loss

FIGURE 11 Handover performance as a function of MAP delay

Simulations with TCP traffic

TCP protocol provides reliable transport connection with the use of acknowledgments. Basic TCP implementations might result in retransmission of the packets that have already been received successfully. We used SACK (Selective Acknowledgment) TCP [60], that enables better throughput because of selective acknowledgments provided by the receiver. [2]

Simulation scenario is the same as presented before (see Figure 9). The CN-BR delay is 200ms and R1/R2-BR delays are 10ms. This time one mobile node MN(0) receives SACK TCP based FTP traffic from one corresponding node. The MN moves with a deterministic path through all BSs. All of the other MNs carry CBR traffic and move with random path. We look closely at the TCP behavior from the CN's point of view in one L3 handover. Figure 12 presents the results with Mobile IPv6 and FFHMIPv6 handover methods. Sequence numbers sent and acknowledgment received are presented as a function of time during one specific handover. With FFHMIPv6 handover method the packet loss during handover is significantly smaller. In addition, SACK TCP eliminates the successful duplicate transmissions providing a better throughput and survival from the

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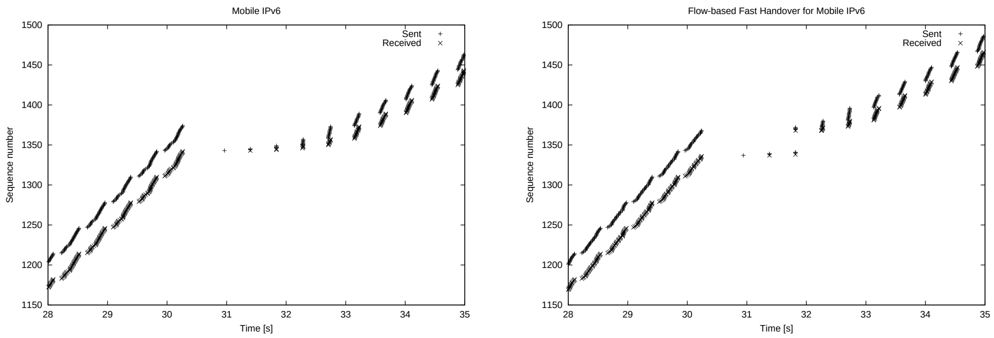
[2] In SACK TCP only the errorneous segments are retransmitted, while normally in TCP all segments have to be retransmitted after one errorneous segment.

handover packet loss, even though the TCP congestion window size is reset to zero due to packet drops according TCP specific congestion control algorithm. The TCP behaviour in packet loss situations depends on the TCP mode and related algorithms. [3] With MIPv6 almost one congestion window amount of packets (˜ 40) are lost, whereas with FFHMIPv6 only a few packets (˜ 3) are lost.



(a) Mobile IPv6

(b) FFHMIPv6

FIGURE 12 Handover performance with TCP based traffic

Simulations with FFHMIPv6 fast upstream

Next, the FFHMIPv6 upstream enhancements are simulated with a ns-2 simulator. The simulation environment is presented in Figure 13 and it consists of two hierarchical Access Networks that are connected to each other with a link (i.e. two mobile networks in different places). The Access Networks are similar to those in earlier simulations, but now there are two of such Access Networks combined. In these simulations the effect of the number of MNs per BS to the network load is also studied. The number of MNs connected to a BS is varied from 1 to 12.

The network carries TCP based FTP, UDP based CBR and VoIP traffic. The bit rate of CBR was 100 kbps and VoIP traffic was generated from exponential divided traffic with a data rate of 88 kbps, burst time of 1.004s and idle time of 1.587s. Every node is communicating with only one CN which resides at the other Access Network and have only one type of application running. Each type of traffic is equally distributed. The results are presented as a mean of 10 simulation repetitions for one MN-CN pair. The duration of the simulation was 160s.

The node pairs start traffic with a random value of 1-10 seconds from the startup. The MNs are randomly distributed to the coverage area and the movement is realized with the random waypoint mobility model. The MN observed is positioned to the exact location of its HA and its path is set to travel directly from one BS to another, then reversing the path. The observed node's CN is kept

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[3] In this case the TCP window size is reset to zero, but by some other TCP algorithms (e.g. congestion avoidance) the window size is divided by two due to packet drops.

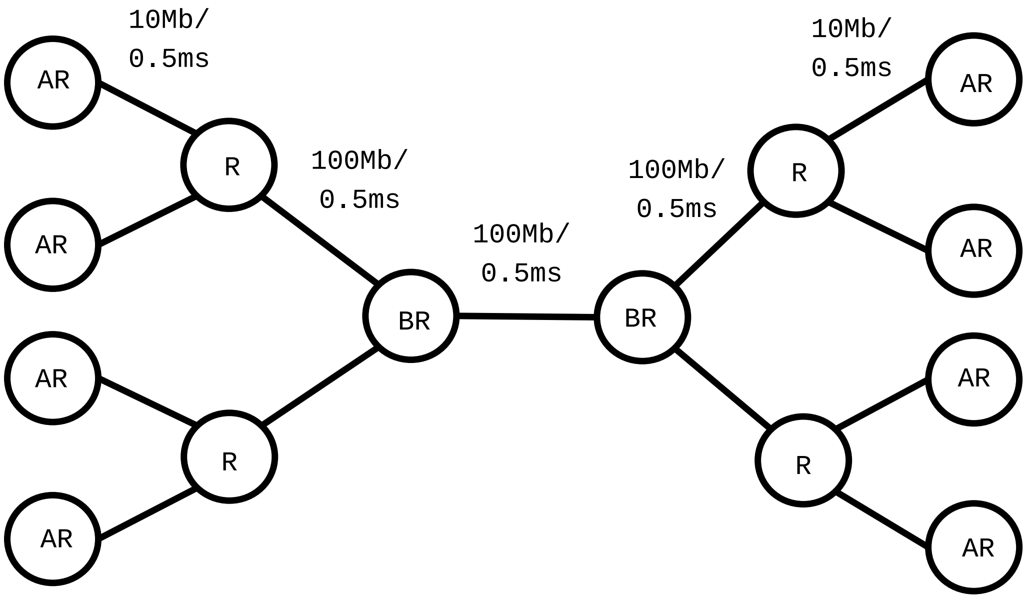

FIGURE 13 Scenario for Upstream Simulations

stationary at its base station to ensure that the CN does not leave its coverage area.

In the FFHMIPv6 upstream proposal the L3 handover packet loss is very important. The quicker the upstream L3 handover is completed, the fewer packets are dropped (or delayed) in this phase of subnet connection change. As can be seen from Figure 14, the fast upstream of FFHMIPv6 is outperforming the MIPv6, because the AR, which is providing the temporal HofA, is located always only one hop away. The increased traffic load still affects also FFHMIPv6 with the fast upstream due to increased waiting time caused by the IEEE 802.11 MAC protocol. This is why the difference between the MIPv6 and FFHMIPv6 is not as noticeable as in the case where there exist only about 2 nodes per base station.

For the FTP traffic using the TCP protocol the most important value is the bandwidth obtained by the receiving mobile node (Figure 15). As we can see, the difference is too small to make a significant impact. The reason is that TCP regulates the amount of bytes sent according to network capabilities. As binding update delay time is insignificant compared to total simulation time, it plays only a small role in the impact on FTP bandwidth. In this respect there is an advantage for FFHMIPv6 when compared with MIPv6.

As the purpose of MIPv6 is also to allow VoIP services, we studied the ratio of the received data to the transmitted data which corresponds to the End-to-End packet loss in the VoIP traffic. The FFHMIPv6 seems to be more efficient in this scenario (see Figure 16), even though the increased traffic load of course affects the packet loss. Also, it is hard to find out where this packet loss takes place in the End-to-End communication chain. But, as Figure 14 showed in the case of CBR traffic, one significant factor is handover delay and the corresponding packet loss.

For more details on FFHMIPv6 upstream simulations, refer to publication

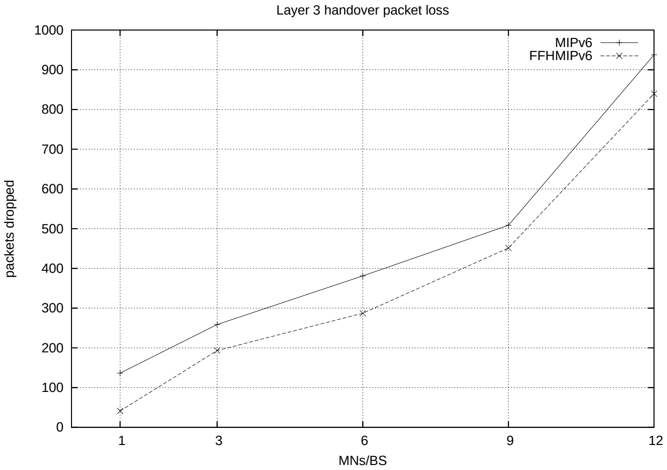

FIGURE 14 Upstream packet loss due to the handover

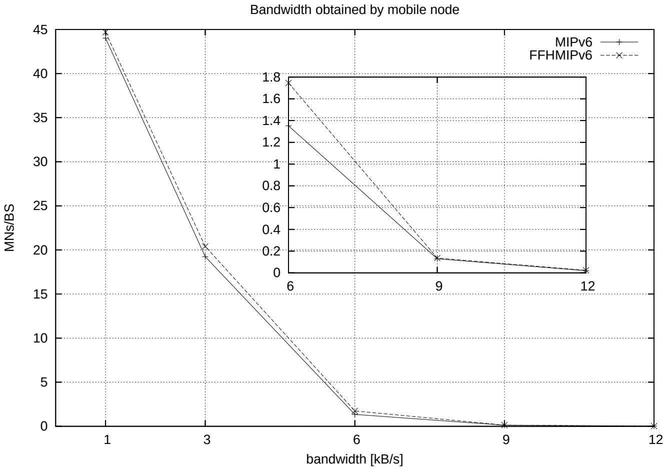

FIGURE 15 Bandwidth obtained by the Mobile Node

[PVII].

2.4.5 Real-network testing

In this subsection we move to a real network environment in order to test the FFHMIPv6 handover method in practice. We compare its handover performance to a Mobile IPv6 implementation in the MIPL (Mobile IPv6 for Linux) [62] environment. We have studied the effect of increasing the distance of the CN from the MN, in a similar manner as in the ns-2 simulations. For more MIPL analysis details, refer to publication [PIV].

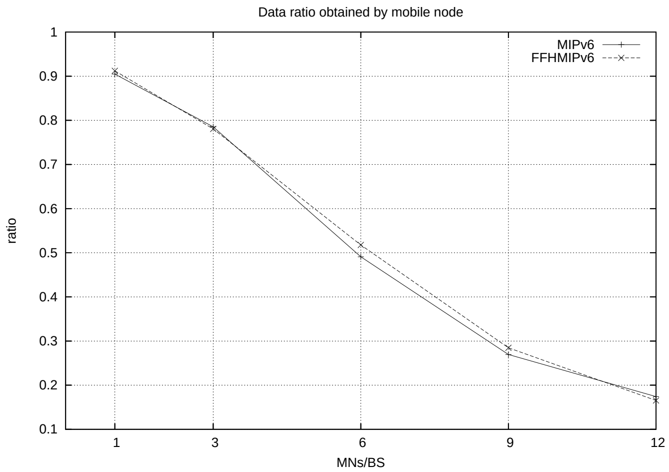

FIGURE 16 VoIP data ratio

Test environment

The test environment consists of seven PC computers. Four of them are configured as routers, one as a Mobile Node and one as a Correspondent Node. The 7th computer is used as a delay component between the main router and the CN.

The delay component computer has a RH Linux version 7.3 as its operating system, with a kernel version of 2.4.18. The other computers run RH Linux 9.0 with a kernel version of 2.4.22 as their operating system. The kernels were updated from standard version 2.4.20-8, because MIPL is built on top of the newer version.

The test scenario is shown in Figure 17. The scenario is built to be hierarchical, just like most of the real networks. There are 3 access routers from which one is also HA (thus there are 1 home network and 2 visitor networks). The objective is to study the effect of increasing the distance between CN and MN to the handover delay with the basic MIPv6 protocol and to find out how much the FFHMIPv6 method improves handover performance in a real environment.

The increasing distance between CN and MN is simulated using a *NIST Net* [78] network emulator, which allows a single Linux PC to be set up as a router to emulate a wide variety of network conditions. In this case the NIST Net causes a user specified delay to the network traffic it routes. Because the software is implemented on top of the IPv4 protocol and the test network is using IPv6, there is a static IPv6-in-IPv4 tunnel between the CN and R1.

In the tests, MN performs the handovers between visitor networks and Return Routability is in use. When the MN is moving from the home network to the visitor network, the FFHMIPv6 method is not used, because it does not have any of the addresses of the CNs in its BU list. So FFHMIPv6 is functioning exactly like MIPv6 in this situation.

MN uses Ethernet access technology; so the handovers are made by plugging in and out the Ethernet cable between different switch segments. This plugging phase cannot be done in a constant time, which is also the case if IEEE

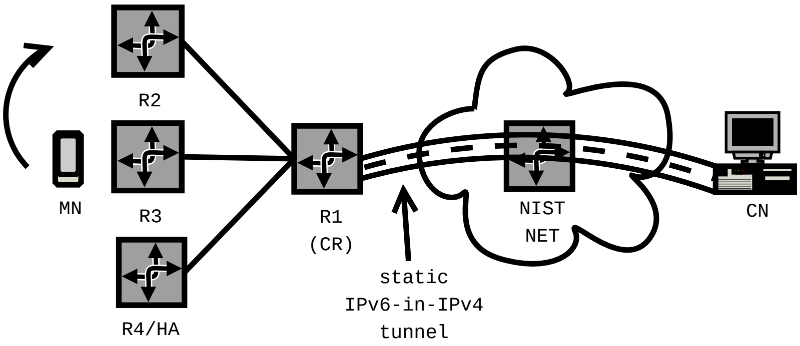

FIGURE 17 The analysis scenario

802.11b WLAN access points were to be used. WLAN handover varies also too much to get reliable results [64]. This is the reason why we calculate the handover delay from the time the MN sends a BU message towards the HA to the time when the first packet is received via the new AR.

Distance of the CN

In order to analyze the effect of the CN distance to the handover delay, the NIST Net delay is assigned values 0, 10, 30, 50 and 70 ms. The CN sends UDP based CBR traffic to the MN with a packet size of 128 bytes and a packet sending interval of 1 ms.

The handover between visitor networks was performed ten (10) times with each of the NIST Net delay values. The results of the tests are shown in Figure 18. Between the handovers the MIPL (and the FFHMIPv6 in cases it was used) was restarted in order to obtain reliable results.

With the MIPv6 protocol the handover delay rises linearly when the delay between the CN and the MN is increased. With the FFHMIPv6 method the handover delay is much shorter than with the MIPv6. That is because the Crossover Router is always found near (router R1). The data flow heading for the old CoA of the MN is found from the routing cache of router R1 and all the packets are tunneled to the new CoA of MN.

The delay stays in about 3-4 ms when using the FFHMIPv6 method, regardless of how big is the delay caused by NIST Net (or how far the CN is located). This is the case in networks, that are built hierarchically. Note that with MIPv6 the delays include the RR procedure, which increases the registration delays by about one third.

2.4.6 FFHMIPv6 security

Each time a new modification or new mechanism is added to the Mobile IPv6 protocol it must be made sure that it does not compromise the security and integrity of the existing protocol. We have analyzed the possibly of new security threats that the FFHMIPv6 induces when implemented on top of Mobile IPv6.

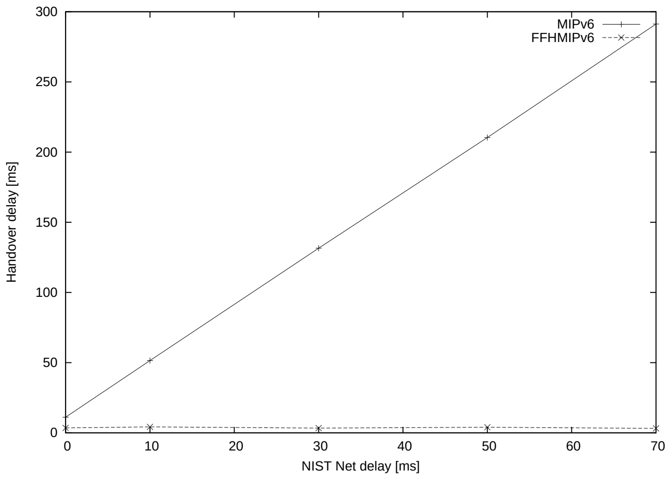

FIGURE 18 Handover delay as a function of NIST Net delay

The FFHMIPv6 method presents one extra threat compared to MIPv6: how the crossover router can ensure that the FFHBU message originates from the correct MN. The Crossover Router has no knowledge of which old CoA and new CoA correspond to the same host, thus it is possible that an attacker could redirect the flows to an incorrect location by creating false FFHBUs. The attacker could receive the unauthorized flows for a lifetime of the FFHMIPv6 tunnel (e.g., 500 ms). The MN should be able to be identifiable on host basis rather than on the CoA, which changes from one subnet to another. Because the AR does not know what new CoA in FFHBU correspond to a specific old CoA, it is impossible to use IP Security (IPSec) Authentication Header (AH) [51].

There are two possible ways of solving the security problem: the first is based on beforehand authentication and the second on trusted third party. Beforehand authentication is based on a host specific identification (id), of which all of the routers in between MN and HA are aware of. This id could be passed to the routers within BU messages, and at that phase the identity of the MN could also be checked with IPSec AH. When the MN performs the handover according to FFHMIPv6, the FFHBU would include this unique identifier. As the FFHBU arrives to a Crossover Router, the identification is compared with the id binding list of the router. If the identifications (old CoA-id binding) match, the tunnel can be created. The problem with this approach is that all of the routers need to be able to store the id-old CoA bindings. The use of authentication server is based on trusted third party. A secret key received from an authentication server is added to the FFHBU message. Before the Crossover Router creates a tunnel, it would verify the FFHBU with the authentication server, in a similar way as in [86]. It remains as future work how much the security procedures would affect the performance of the FFHMIPv6.

There are also other security risks, which are not directly related to FFHMIPv6. These are related to the security of the underlying system and thus they are not discussed here. For more details FFHMIPv6 security, refer to publications

[PVI] and [PVIII].

2.4.7 Discussion

Mobile IPv6 protocol is seen as the mobility management protocol for the upcoming 4th generation networks. Already the 3G LTE core is based purely on the IP protocol, thus it is likely that a Mobile IP protocol is to be used to solve the mobility management. To support applications with strict QoS requirements, the handover procedures must be seamless to the applications. For example, VoIP applications need strict delay bounds in both communication directions. We have designed FFHMIPv6 with upstream enhancements to support seamless handovers. The aim of the enhancements has been to create a L2 independent protocol, to reduce complexity in a heterogeneous access environment. But, for true seamlessness and other 4th generation requirements (such as multihoming and ABC connections) link layer support may be necessary after all. Also, due to the heterogeneous nature of the 4th generation networks with several overlapping access technologies, the FFHMIPv6 might not be the best possible alternative. It is expected that the communication path might change quite a lot during vertical handovers, which could make locating the Crossover Router difficult.

The FFHMIPv6 method is designed to be used as a micro mobility solution. Network topologies are often built hierarchically, so that all of the domains' ingress and egress traffic pass through the same router (Border Router). Given this assumption, the Crossover Router would, very likely, be found in most networks. Thus, with one BU message we could redirect all of the MN's flows, whether they are tunneled flows from HA or direct flows using route optimization. Also, as a fallback, if the flows were not found from the flow cache of the routers or the routers did not support FFHMIPv6, normal MIPv6 BU process would be applied. It is also worth noting that in FFHMIPv6 the processing of the fast handover procedures (basically tunneling) is divided amongst several routers, based on the flow paths and CR locations.

The FFHMIPv6 causes some processing delay due to Hop-by-Hop header processing in the routers. Hop-by-Hop extension header is a feature provided by the IPv6, thus the processing delay is not directly caused by the FFHMIPv6 method itself. Also, according to our preliminary studies in publication [PVIII], the FFHMIPv6 processing delay (including creating FFHBU and Hop-by-Hop header processing) is negligible (< 1 ms), at least in light load conditions.

FFHMIPv6 requires the flow cache features from the network routers. This might also induce some scalability problems, because the routers store flow level information. But, at least Linux, Cisco (IOS) and Juniper (JUNOS) already include the flow cache properties. For speed issues, it is important of course, whether the flow cache is implemented in the hardware or software. At least Cisco Catalyst 4500, 5000 and 6500 series switches and 7500, 10000 and 12000 series routers implement the flow cache in the hardware. The maximum entries in the cache vary from 250k to 1M. The flow caching methods can be either based on pure per-flow information or on statistical sampling. And, with no doubt we expect that even more intelligent cache implementations will be available in the future. These issues assure that the FFHMIPv6 only uses the existing intelligent flow cache facilities and is therefore not directly linked to these scalability problems.

FFHMIPv6 improves only the CoA registration phase of the Mobile IPv6 protocol. Other MIPv6 handover procedures are not affected in any way. However, FFHMIPv6 can be utilized in conjunction with other Mobile IPv6 enhancements to provide the best handover performance (e.g. FMIPv6, Fast RAs, oDaD).

2.5 Summary

In this chapter the Mobile IPv6 functionality and performance is presented in a homogeneous environment (i.e. one access technology in use). The basic Mobile IPv6 procedures require too much time for QoS sensitive applications, being in the order of several seconds. Numerous enhancements have been proposed in the past few years, and the Hierarchical Mobile IPv6 and Fast Handovers for Mobile IPv6 designed in the Mipshop IETF working group are seen as the most promising ones. We propose the Flow-based Fast Handover for Mobile IPv6 as one possibility to be used in the 4th generation networks and analyze its performance in theoretical, simulative and real-life environments. The analysis scenarios consider the FFHMIPv6 performance at its "best" and "worst" as well as showing its main benefits in providing handover delays independent of the communication delays between its communication parties. Also, the security aspects of FFHMIPv6 are discussed as well as some possible problem points.

3 TOWARDS CONVERGING NETWORKS

In this chapter we present the basic Mobile IPv6 functionality and performance in heterogeneous environments. The most essential converging networks related research is presented in the following section. Based on our own work, the usage of link layer information and its benefits in handover context are discussed in section 3.3 and the interface selection procedure (algorithms) and their analysis is presented in section 3.4. Finally, VERHO intelligent handover controller architecture is presented, with some future enhancement ideas and benefits.

3.1 Mobile IPv6 in heterogeneous environments

As presented in the previous section, Mobile IPv6 functions quite well in horizontal handovers, especially when applying some enhancements, such as Fast Handovers for Mobile IPv6 [54] or Flow-based Fast Handover for Mobile IPv6 [PI]. However, related to multi-access devices in heterogeneous environment, Mobile IPv6 faces some additional challenges. For example, how to decide which link should be used by Mobile IPv6 when there are several available links? How to provide the users with various preferences the possibility for Always Best Connected access?

Mobile IPv6 has been analyzed in combined IEEE 802.11 and GPRS environment with TCP traffic in [16]. The authors also propose and evaluate few network layer optimization techniques to improve the vertical handover performance. The difference in link layer characteristics of WLAN and GPRS (e.g. RTT and bandwidth) cause poor performance. Buffering and RA caching are found to improve the performance for some applications.

Similar kind of analysis is presented in [5] consisting of Mobile IPv6 handovers between WLAN and GRPS. The authors have quite a practical view on how the GPRS can be utilized without problems with NAT and firewalls. The authors claim that there are no significant packet losses in handovers between GPRS and WLAN. Nevertheless, the different throughput and RTT characteris-

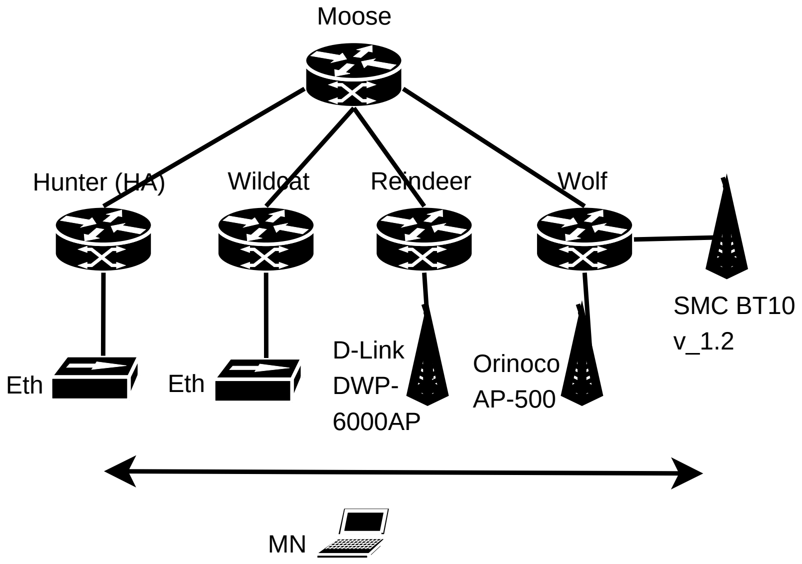

FIGURE 19 The MIPL2 test network

tics might create problems for some applications.

Mobile IPv6 real-life testing

Mobile IPv6 implementation for Linux (MIPL) [62] version 2 release candidate 3 was used in testing. The MIPL2rc3 is patched with our bug fixes to allow it to operate better in a multi-access environment. The MIPLv2 implementation was chosen because it is open source, for Linux OS, and constantly maintained.

The test network is presented in Figure 19 with Ethernet, IEEE 802.11b and Bluetooth access technologies. Ethernet link connected to Home Agent (Hunter) is the Home Network (HN) and other links are Foreign Networks (FNs) related to Mobile IPv6. Three types of handover tests were performed; horizontal handover and vertical handover performance tests as well as interface selection tests. Horizontal handovers included Ethernet to Ethernet handovers and WLAN to WLAN handovers. Vertical handovers include Ethernet to WLAN and Ethernet to Bluetooth handovers. For details about the analysis environment as well as the results refer to publication [PIX].

All of the handover delay results are presented in Table 5. The movement detection is performed by the MN sending the *Router Solicitation* message to which the AR responds with a *Router Advertisement*. The Link Down event from the device driver triggers the solicitation. In [74] it is specified that AR has to wait a random time between 0 and 0.5 seconds. In vertical handovers (i.e. Eth-WL, Eth-BT) the movement detection time is nil when moving to foreign network, because the target interface has a valid IPv6 address when Ethernet link is put down.

The CoA configuration phase is a result of the DAD process of a new CoA of the MN. In DAD the MN sends a *Neighbor Solicitation* to the new CoA and then it waits for a second for response. If no response is received, the CoA is

TABLE 5 Handover delays in MIPL network

		Mov.det.	CoA conf.	CoA reg.	HO delay
Eth-Eth	HN->FN	0.96	1.61	1.01	3.58
	FN->HN	1.00	1.25	0.11	3.36
WL-WL	FN->FN	1.31	1.27	0.02	2.60
	FN->FN	1.71	1.32	0.02	3.05
Eth-BT	HN->FN	0.00	0.01	1.04	1.05
	FN->HN	1.07	2.00	0.12	3.19
Eth-WL	HN->FN	0.00	0.01	1.01	1.02
	FN->HN	0.66	1.74	0.11	2.51

considered valid. The CoA registration delay consists of binding process to the HA, thus Binding Update to the HA and Binding Acknowledgment in response. A round-trip propagation delay to the HA causes the delay. When the MN moves to a foreign network the HA performs DAD to verify the validity of the HoA.

The overall delays sum up to over 3 seconds, which is quite alot taking into account that this is calculated from the signaling messages and without any congestion in the network.

Always-Best-Connected access can be thought from two aspects; horizontal and vertical. The purpose was to find out how the MN chooses the AP in the horizontal handover case. The network has two APs configured with the same Extended Service Set Identifier (ESSID), but the other one is configured as 2Mbps AP and the other as 11Mbps AP. The MN has got a WLAN interface in down state and then it is put up. The purpose is to see how the MN chooses the AP to use. From 10 repetitions we found out that both APs are chosen in an equal probability (i.e. 50%). This shows that MN randomly picks up an AP if it only has the correct ESSID and its signal strength is above the driver defined threshold (in this case 11 Signal to Noise Ratio, SNR).

The Mobile IPv6 specification [46] does not take into account interface selection in a multi-access environment at all. A MIPL implementation on the other hand includes interface specific static priorities, where the link with the biggest priority will be chosen. This approach might be suitable in an environment, where we have two technologies available, but for more complex situations it might not be flexible enough. In a true heterogeneous environment there might exist several access technologies and several APs within the coverage. Also, these APs might provide different quality, which might be a subject for a quite rapid change because of multipath radio environment. End-to-End paths to CNs differ depending on the AP location in the topology. Different users might have different preferences for the access in use, e.g. cost, coverage, bandwidth. The best connectivity also relates to the applications in use, e.g. VoIP, IP-TV, file transfer. This kind of more complex environment calls for more enhanced interface and AP selection.

3.2 Related converging networks research

In this section the most essential work related to Mobile IPv6 analysis and enhancements related to multi-access environments are presented.

One of the first publications related to handling vertical mobility in heterogeneous environments is presented in [101], where the authors mainly consider vertical handover performance presenting some enhancements to Mobile IP (MIP), such as fast beaconing, doublecasting, etc. They also discuss the tradeoff between handover delays, power consumption and signaling bandwidth. As a part of this work a policy based vertical handover system [117] is proposed.

Different procedures, algorithms and metrics related to heterogeneous wireless environment are discussed in [125]. The paper presents a handover algorithm usable when using two access networks: a cellular WWAN network and an accompanying WLAN network. The general idea is to use WLAN when available and the cellular network in the other times.

A policy based Mobile IP handoff decision (POLIMAND) mechanism utilizing Generic Link Layer [96] and pre-defined policies is presented in [6]. The paper mainly considers Mobile IP performance, and the real life experiments show that POLIMAND outperforms pure Mobile IP in terms of handover delay and packet loss.

Also, a policy-based interface selection procedures and architecture are presented in [126]. The architecture takes into account different input parameters, such as link layer, IP layer, network originated and user/application information. The authors discuss the differentiation of policies and the actual mechanisms which enable the dynamic interface selection. To support the discussion they have extended Mobile IPv6 to support multiple HoAs allowing simultaneous access (SIMA).

A MIMP architecture (Multiple Interfaces Management Protocol) is presented in [4]. MIMP gathers input information from each access technology, users and applications and calculates the best way of spreading the current flows amongst the available interfaces (i.e. providing simultaneous access). MIMP uses an enhanced version of Mobile IPv6, which supports utilizing several links simultaneously.

The authors in [50] discuss ways of enhancing the Mobile IP protocol for faster vertical handovers. They have implemented an architecture similar to that of [4] and [126], but their primary focus is on handover delays in multihomed hosts. They enhance MIP with several proposals, such as proactive triggering and soft handovers, and, according to simulations, handover delay is reduced from about 2100 ms to 30 ms.

A Device Convergence Layer (DCL), which hides the multiple interfaces and links from the Mobile IP stack by creating a DCL virtual interface, is proposed in [55]. DCL interface is always used by MIP regardless of how many interfaces the terminal might have or use. DCL handles vertical handovers leaving only horizontal ones for MIP. According to real life experiments, a tight integration utilizing soft handover concept achieves a thoroughly seamless connectivity.

Quite extensive policy based system called PROTON (Policy-based system to ROam Transparently among Overlay Networks) for heterogeneous environments with a highly dynamic nature is presented in [111] and [110]. The system consists of context management (cross-layer input and profiles), policy management and policy enforcement to support IP based mobility in 4G networks. In a use case scenario with real life experiments and discussion the system is found to be flexible and efficient.

Mobile IPv6 extensions to support multiple interfaces and policy-based routing are proposed in [116]. Multiple interfaces can be used by utilizing several HoAs improving for example throughput and fault tolerance. Policies are used to divide different flows among the available interfaces. This work is an early step on Multiple CoA registration work performed in IETF Monami6 charter.

An Adaptive Handover Control Architecture (ACHA) to enhance handover performance and wireless access utilization in heterogeneous networks is proposed in [84]. The architecture is designed to be modular, so that different modules can be designed independently. But the paper actually does not propose any mechanisms in detail.

OmniCon Mobile IP based vertical handover system is presented in [98]. The solution focuses quite strictly on IEEE 802.11b and GPRS links and mainly on problems induced by GPRS, such as Network Address Translation (NAT). The interface selection is handled simply by preferring WLAN over GPRS.

An End-to-End mobility management system for seamless and proactive roaming across heterogeneous environment is presented in [34]. The system consists of a connection manager and a virtual connectivity based mobility management scheme. The former detects the condition of wireless networks and the latter maintains connection continuity using the End-to-End principle. The practical experimentations with GPRS, IEEE 802.11 and Ethernet show that the system can handle proactiveness and seamlessness. The drawback of the mobility management system is that it is a dedicated solution with a restricted deployment potential.

The Mobile IPv6-IPv4 interoperability as well as Mobile IPv6 vertical handover performance are discussed in [10]. The authors show that a link layer triggering the overall handoff delay can be reduced to less than 0.2 seconds while utilizing two interfaces.

Our work related to All-IP mobility management through this dissertation is similar to the research work discussed above and indeed the vision and research problems are the same. However, we aim at solving the mobility management bottom-to-top handling all necessary entities, starting from efficient mobility management and real-time link information and ending at good end-user experience with always-best-connected access and efficient mobility aware applications. Also, we use quite practical approach to enable us to try all the ideas in practice by prototyping on top of open platforms. However, the vision is not yet fully achieved, thus some future work ideas are presented in section V.

3.3 Utilizing link layer information

Different access technologies, such as IEEE 802.11 (WLAN), provide link layer handovers, i.e. handover between the Access Points (APs) of the same technology in question. IEEE 802.11 specifies the active and passive AP scanning processes, which provide information about the available APs in the neighborhood. The actual connection with the APs is handled with a two-way association process. Bluetooth does not specify any handover mechanisms, although it provides some tools to perform it. By using Bluetooth in the Personal Area Network (PAN) mode and Service Discovery Protocol (SDP) we can implement the Bluetooth handover by ourselves. IEEE 802.3 (Ethernet) is in general simpler, because a handover consists of plugging in and out the cable. Also cellular networks, such as Universal Mobile Telecommunications System (UMTS) and General Packet Radio Service (GPRS), provide IP based communication and link layer handovers.

As a link layer handover preceeds the Mobile IPv6 handover, a cross-layer information (e.g. triggers or hints) from the link layer could speed up the MIPv6 handover procedures. For example, in [6] the POLIMAND system utilizes the link layer information from a Generic Link Layer (GLL) [96]. GLL is a shim layer between the link layer technologies (e.g. IEEE 802.11, cellular technologies) and an IP layer providing unified link layer information for the upper layer mobility management protocol. With the hints from GLL, POLIMAND can perform the handovers with Mobile IP with less delay and packet loss. In [69] the authors claim that link layer control frames (at least from IEEE 802.11b) could be utilized for anticipating the handovers and thus processing some of the Mobile IP processes in advance.

We agree that the link layer can be utilized in anticipating the handovers and thus resulting in faster overall handover delays. But, some questions needs to be answered, including: How this could be done in a real system? Thus, what parameters can be gathered without modifications to existing access technologies? How the information can be utilized in the handover context? The link layer information can also be utilized in the interface selection procedures due to the real time information of the link status as well as link quality.

3.3.1 Listening to link layer status and quality

The information that can be gathered from the link layer can be divided into two categories; events and parameters. Event provides information about what happens at the link layer (e.g. connected, disconnected, AP-in-range) and parameters about the quality and features of the link. The parameters can be divided into static, configurable and quality related. Static parameters are unchanged variables usually related to physical interfaces (e.g. interface identification, MAC address). Configurable parameters are usually related to the current link or IP level configurations (e.g. network name, IP address of an interface, IP address of an AP). Parameters related to quality can include signal strength, QoS parameters

TABLE 6 An example of parameter division

Parameter type	Parameter	Example
Static	IFId	eth0, bnep0, wifi0, ppp0
	IFType	Ethernet, BT, WLAN
	IFMacAddr	00:60:1D:23:39:C3
Configurable	IFStatus	IFUp, IFDown
	IFIpAddr	3ffe:1::3/64
	NetworkName	MyNetworkName
	BSSID	00:E0:03:05:3A:CD
	Channel	1-13
	APIpAddr	3ffe:1::2/64
	GWAddr	3ffe:1::1/64
Quality	SigStr	40dB
	PowLevel	10 mW
	BitRate	11 Mbps
	Security	WEP,WPA
	AvBandw	6 Mbps
	Price	1 euro/MB

or features the link offers. See Table 6 for examples of the parameters based in the above division (note that not all of these can be gathered from link layer). For more information about possible link layer information events and parameters, refer to publication [PX].

However, different access technologies might provide different events and parameters in different forms, and not every interface will provide the same parameters. For example, Ethernet does not provide any value for signal strength. Thus, it is necessary to unify these parameters for the upper layer if the parameters are presented in different scale, format, etc. In this context the unified values for events and parameters are called triggers and hints. Triggers and hints can be considered to be functional in the MN, AP and AR side, but in this dissertation mainly the MN side is considered.

Trigger is defined as unified information that presents the events that take place in the link layer, such as association or disassociation to an AP. Hint is more quality related and can provide certain extra information (e.g. signal strength) to the upper layer to enable it to anticipate shortly occurring events. The IETF DNA working group has specified two triggers: *Link Up* and *Link Down*. Link Up signifies a state change associated with the interface becoming capable of communicating data packets (e.g. IP packets). Link Down on the other hand signifies a state change associated with the interface no longer being capable of communication data packets.

Another question is how the triggers are created from the link dependent events. In [124] the authors, who participate in the DNA working group, discuss how the triggers can be formed from GPRS, Code Division Multiple Access 2000 (CDMA2000) and IEEE 802.11 link layers. In GPRS they can be formed from a successful activation/deactivation of a Packet Data Protocol (PDP) Context, in CDMA2000 IPV6CP from opened/closed state and in IEEE 802.11 from a successful association/disassociation with an AP. For Ethernet the triggers are generated immediately after plugin/plugout, but the Spanning Tree Protocol (STP) will cause about 30 seconds delay after this, thus the Link Up should be generated only after the STP is finished. [1]

Hints can be defined as pure parameter values passed onto the application (signal strength = 2) or they can be specified hints according to the parameters (e.g. Link Coming Up, Link Going Down, Link Available).

The link layer information can be utilized by different mobility management protocols for different purposes or by some application to build wireless network status and quality awareness, e.g. for adaptation purposes. In the next list, the benefits in utilizing the link layer information in the handover context are presented.

- Triggers – Mobile IPv6 movement detection is quite slow if utilizing only L3 procedures. If handover trigger is generated from the link layer when the link layer handover procedures have ended, the MIPv6 can react by immediately sending Neighbor Solicitation (NS) to the new Access Router to get new subnet information.
- Hints – Hints themselves can be formed from signal strength or positioning information. The purpose is to get information about possible upcoming handovers before they actually happen (i.e. make-before-break handover). This anticipation enables the mobility management protocol to perform some of its handover procedures beforehand (e.g. form a new IP to the NAR), thus reducing the handover delay.
- Parameters – By parameters we mean pure parameter values that are gathered from the link layer. This information can be utilized in the interface selection in arranging the links into preference order.

3.3.2 Access Point Scanning

As said before, the access technologies might provide their own AP scanning mechanisms. For example IEEE 802.11 supports both active and passive scanning. Active scanning is performed by probing the environment actively with MAC layer procedures; in passive scanning the MN listens to the beacon messages sent by the AP. The performance of AP scanning related to IEEE 802.11 is out of scope of this dissertation, but for related research refer for example to [93] and [119].

The horizontal AP selection in the link layer is usually performed by the device driver (of the specific technology) on the basis of signal strength and related

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[1] STP has been standardized by IEEE 802.1D to prevent loops in switched networks

thresholds and hysteresis. We claim that the AP selection should be made based on other parameters as well, since the signal strength is not giving all the tools necessary for ABC. APs might be experiencing different load conditions based on the amount of attached MNs and their applications. The APs might also offer different link layer security mechanisms. Also, the APs might be connected to different subnets, which affects the need to perform the time consuming MIPv6 handover.

Currently, the link layer AP scanning provide quite limited range of parameters, mainly necessary for the L2 handover to take place (e.g. SNR, Tx power, security). But, some possible enhancements for the L2 scanning procedures are presented in section 3.6. There are two possible ways to solve this; enhancing the access technology to support more parameters or gathering extra information from L3 signaling, such as Candidate Access Router Discovery (CARD) [57].

3.4 Interface selection

Traditionally, mainly related to horizontal handovers, the handover decision is made purely according to signal strength. Usually this means signal strength thresholds and some hysteresis (or dwell time) to avoid ping-pong handovers [92], [83]. This solution is feasible when we consider homogeneous WWAN networks, which provide almost complete coverage and good Radio Resource Management (RRM) procedures to ensure fair treatment and necessary QoS. However, this is neither sufficient nor suitable to satisfy users with different preferences in a heterogeneous multi-access environment [61]. The WLAN and WPAN networks are built as hotspot areas by a variety of wireless service providers as well as companies, communities and individual users. Thus, the heterogeneous environment varies constantly in availability, provided services and Quality of Services. More intelligent decision making is required to fulfill the user needs.

When there are several attributes affecting the interface selection, the procedure itself turns out to be a little more complex. Several link status, quality and feature related parameters as well as user preferences need to be taken into account. Static link specific priorities are not enough to provide the selection when users with different preferences and constantly changing heterogeneous radio environments are considered. The interface selection process itself can be described as a Multiple Attribute Decision Making (MADM) problem [17], where alternatives (i.e. the links) are characterized by multiple, usually conflicting, attributes.

3.4.1 Related research on interface selection algorithms

An overview of several research projects related to future multi-criteria handover algorithms are given in [104]. Different solutions are compared according to several parameters, such as mobility management support, profile support(user, network, etc.), handover initiative and assisting entities, simultaneous access support, etc. The authors claim that the traditional signal strength or hysteresis algorithms are not sufficient, but some more complex algorithms are needed. The authors suggest a profile based approach and claim that further research is needed for determining the handover triggering time instant as well as affecting MADM parameters.

Different MADM methods, i.e. Simple Additive Weighting (SAW), Technique for Order Preference by Similarity to the Ideal Solution (TOPSIS), Grey Relational Analysis (GRA) and Multiplicative Exponent Weighting (MEW), are compared with four link specific parameters (bandwidth, delay, jitter, bit error rate) in [102]. MEW, TOPSIS, SAW and MEW[2] provide quite similar results, but GRA results in a slightly better bandwidth and lower delay. The importance weights are found to be the most important guide for the algorithm operation.

Also, SAW, TOPSIS and Maxmin MADM methods have been analyzed numerically with simulations in [127]. Fuzzy logic is used to map the fuzzy parameter values into crisp ones before applying different traditional MADM methods. The authors consider mainly the fuzzifying mechanisms. In simulations TOPSIS is found to be the most sensitive to user preference and attribute values; SAW gives a relative conservative ranking result.

An SCTP based vertical handover mechanism based on evaluated application performance and a utility based handover algorithm is presented in [79]. The way of monitoring the application performance is interesting, though forms a drawback in a sense that the solution is application dependent. Some general proxy with standardized interface would be needed to communicate between the applications and the mobility management implementation.

In [30] the authors claim that both access network status and the Quality of Service are important to take into account in the network selection as they are related to overall network capacity. The authors propose also two related algorithms. However, this research is only cellular network dependent, thus concerning mainly 2G and 3G systems. The applicability of the results into unlicensed technologies is uncertain.

A utility based handover algorithm is also utilized in [82]. The approach is based on a principle where the predicted consumer surplus is maximized while minimizing the application delays. However, the approach does not take into account how different kinds of user preferences can be taken into account related to other parameters.

Quite similar approach as we present on network selection in the following sections is presented in [120]. The system gathers input parameters related to the user, application and access network and utilizes a fuzzy logic controller to choose the best link in similar fashion as in [127].

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[2] MEW is the same algorithm as the Simple Productive Weighting (SPW) presented in section 3.4.4 Equation 5

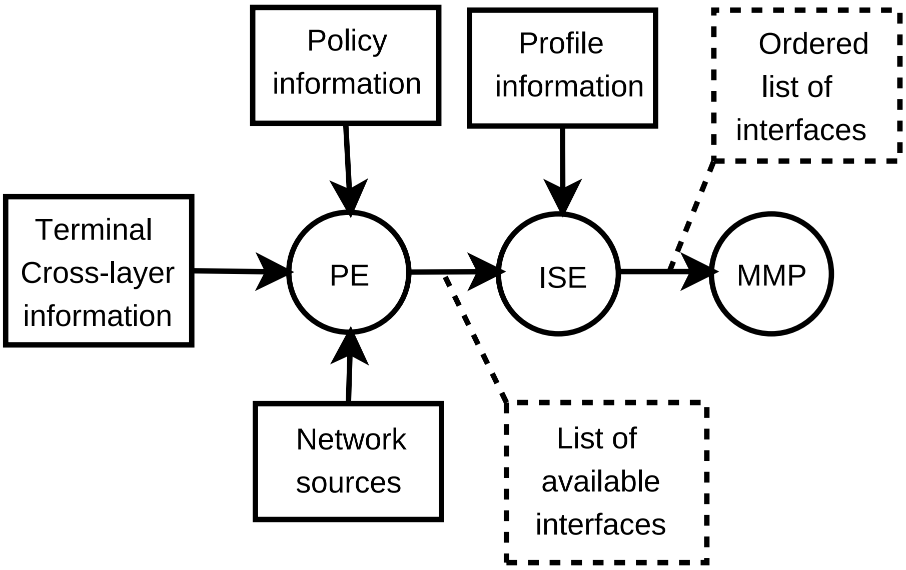


FIGURE 20 Interface selection procedure

3.4.2 Interface selection procedure

The overall idea of interface selection is presented in Figure 20, where *PE* is the Policy Engine, *ISE* the Interface Selection Engine and *MMP* the Mobility Management Protocol.

The policy engine receives the input parameters from different sources, which might include the MN protocol stack (e.g. link layer, mobility management protocol, applications) or external sources (e.g. positioning system). The link layer is utilized as presented in Section 3.3 by providing the link status information. The policies are explicit rules set on a usable interface. A usable interface has to pass all policy rules to be usable in the interface selection. Policies are discussed in the next subsection.

All usable interfaces participate in the interface selection, where a preference value (i.e. a dynamic priority) is calculated for each interface according to the interface specific parameters and a set of profiles (e.g. a set of parameter specific weights). Profiles are set by users to represent their preferences on required link parameters. Later on, also application specific weights can be utilized.

The output of ISE is an ordered list of usable interfaces representing the current heterogeneous link characteristics and user preferences. The utilized MMP performs the standard handover procedures if the best interface has changed. The MMP used in our studies is Mobile IPv6.

3.4.3 Handover policies and profiles

The system uses a policy based approach to decide which available interfaces could and should be used. Policies are enforced by using rules and profiles. Rules define strict parameter specific requirements that every interface must satisfy. If an interface does not satisfy a rule then it is marked as disabled and will not be considered in the further decision process. The policies can be presented in several ways, for example using the Policy Core Information Model (PCIM) of IETF. The policy description itself, however, is out of scope of this dissertation.

The profiles may be specified by different sources which are let to control the used links.

- System – rules related to physical interface and link states (e.g. ifDown, ifUp, linkDown, linkUp),
- Operator – can instruct a group of users to use or not to use a certain link at a certain time (e.g. load balancing during rush hours with a link specific rule),
- User – user can set policies to all parameters (e.g. price, required bit rate),
- Application – some applications require a certain bit rate from the connection for it to work properly.

After applying the rules to each interface the process results in a set of disabled and enabled interfaces.

The ISE rearranges the usable interfaces into preference order taking into account the input profile. The profile is defined as a set of numeric parameter specific weights. Note, that the profiles could also use fuzzy sets of weights (e.g. high, medium, low) or pre-defined mapped values from pre-defined user profiles.

The weights are one of the most interesting issues related to the MADM algorithms as they enable prioritizing different properties over each other. Most likely, the profiles are user defined, but also application specific weights can be taken into account. The overall weights could then be a function of both user and application weights (e.g. a product). Weights of applications can also be dynamic according to e.g. number and properties (requirements) of the application.

3.4.4 MADM interface selection algorithms

The interface selection procedure is an MADM problem, with q number of links (interfaces) representing the alternatives. Each link has p number of properties (or attributes), such as bit rate and cost. A decision matrix $R^t_{q,p}$ represents a snapshot of the links at time t. So, the element $r^t_{i,j}$ of $R^t_{q,p}$ is the value of property j for interface i at time t. We also use R^t_i to represent the ith row of $R^t_{q,p}$ (also $R^t_i = I_i$, the ith interface or alternative). That is, each row corresponds to an alternative and each column to a property.

There exists several different MADM methods, but the detailed description of those is out of scope of this dissertation. For interface selection purpose we present the Simple Additive Weighting (SAW), Simple Productive Weighting (SPW) and TOPSIS methods, and we analyze these algorithms with simulations in the following section. An assumption is made that these are the most capable ones. Other MADM methods can be found from [41].

The weight vector is also called as *profile* and it is represented as

$$weights[w_1, w_2, w_3, \cdots, w_p], \tag{1}$$

where p is the number of parameters. So, each parameter has a weight representing its importance.

The interface selection algorithms take $R^t_{q,p}$ as their input. The *signal strength* based algorithm can be described by equation (2).

$$S^t_{ss} = R^t_l | R^t_{l,s} = \max_{i=1}^{q} R^t_{i,s} \tag{2}$$

where $R^t_{i,s}$ relates to the signal strength value of an alternative i at time t. Thus the interface selected S^t_{ss} is the interface with the best signal strength.

The traditional *priority* based system can be presented by equation (3).

$$S^t_{pr} = R^t_l | R^t_l(pr) = \max_{i=1}^{q} R^t_i(pr), \tag{3}$$

where $R^t_i(pr)$ relates to the priority of the interface i at time t. The interface selected S^t_{pr} is the interface with the highest priority value.

Simple Additive Weighting (SAW) specifies a weight for each property, which is then multiplied with the scaled property value and the overall score of an interface is computed as a sum of the weighted property values. Properties can represent anything from interface name to the cost of the interface. Weights are defined by the user or by the applications' preference settings. The SAW algorithm is presented in equation (4). For calculating the output the elements of $R^t_{q,p}$ are scaled into a common interval (e.g. 0-1). It is necessary because each property may have different intervals for its values. $r'^t_{l,j}$ represents the scaled $r^t_{l,j}$ value.

$$S^t_{saw} = R^t_l | \frac{\sum_{j=1}^{p} w_j * r'^t_{l,j}}{\sum_{j=1}^{p} w_j} = \max_{i=1}^{q} \frac{\sum_{j=1}^{p} w_j * r'^t_{i,j}}{\sum_{j=1}^{p} w_j}, \tag{4}$$

where w_j is the weight of property j.

The *Simple Productive Weighting* method is similar to SAW, but the scaled property values of each alternative are powered by w_j and in order to penalize the alternatives with poor attribute values more heavily, a product instead of a sum of the values is made across the properties. The weighted product is presented in equation (5):

$$S^r_{wp} = R^t_l | \prod_{j=1}^{p} (r'^t_{l,j})^{w_j} = \max_{i=1}^{q} \prod_{j=1}^{p} (r'^t_{i,j})^{w_j}. \tag{5}$$

TOPSIS (Technique for Order Preference by Similarity to the Ideal Solution) is based on the principle that the chosen alternative should have the shortest distance from the ideal solution. In general the process calculates the distances of each property value in the weighted normalized decision matrix from the ideal and non-ideal solutions. The shortest relative closeness to the most ideal solution will be chosen as the best link.

First the decision matrix is normalized with equation (6). Second, the normalized decision matrix is weighted with the parameter specific weights (see equation (1)) with equation (7). Third, an ideal A^* and negative ideal A^- solutions are determined with equations (8) and (9), respectively. Fourth, the separation of each alternative from the ideal solution and the negative ideal solution, S_{i*} and S_{i-}, are computed with equations (10) and (11), respectively. Finally, the relative closeness to the ideal solution is calculated with equation (12). The link with the smallest relative closeness to the ideal is chosen.

$$r_{i,j}^{norm} = \frac{r_{i,j}}{\sqrt{\sum_{i=1}^{q} r_{i,j}}} \tag{6}$$

$$r_{i,j}^{wn} = w_j * r_{i,j}^{n}, \qquad i = 1, \cdots, q, j = 1, \cdots, p \tag{7}$$

$$A^* = [v_1^*, v_2^*, \cdots, v_p^*] = \max_{j=1}^{q} r_{i,j}^{wn}, \qquad i = 1, \cdots, q, j = 1, \cdots, p \tag{8}$$

$$A^- = [v_1^-, v_2^-, \cdots, v_p^-] = \min_{j=1}^{q} r_{i,j}^{wn}, \qquad i = 1, \cdots, q, j = 1 \cdots p \tag{9}$$

$$S^{i*} = \sqrt{\sum_{j=1}^{p} (r_{i,j}^{wn} - v_j^*)^2}, \qquad i = 1, \cdots, q \tag{10}$$

$$S^{i-} = \sqrt{\sum_{j=1}^{p} (r_{i,j}^{wn} - v_j^-)^2}, \qquad i = 1, \cdots, q \tag{11}$$

$$C^{i*} = \frac{S_{i-}}{S_{i-} + S_{i*}} \tag{12}$$

Algorithm simulations

The above presented algorithms are simulated in Matlab environment to understand their suitability for interface selection purposes. The MADM methods are compared against the traditional signal strength and static priority based approaches. We use the notation introduced in the previous chapter.

All the presented interface algorithms are using a priority algorithm (see equation (3)) as a fallback in the case of having the same preference value for several interfaces. The order of preference is then Ethernet, IEEE 802.11, Bluetooth and finally cellular.

We take into account six properties for each interface, namely signal strength, bit rate, power consumption, price, coverage and security. We have four interfaces; IEEE 802.3 Ethernet (10Mbps/100Mbps) as I_1, IEEE 802.11b/g WLAN

(11Mbps or 54Mbps) as I_2, Bluetooth (v1.2 or v2.0) (723kbps/2.1Mbps) as I_3 and cellular link (i.e. GPRS, EDGE or UMTS) (from 80kbps to 384kbps) as I_4. Each of the interfaces have the above presented properties that suit the reality of the link technology. Only the access interfaces are considered, and not the End-to-End quality. An interface *i* at time *t* can be represented by a vector

$$I_i^t = [ss, br, pc, cost, cov, sec], \tag{13}$$

where *ss* is the signal strength, *br* the available bandwidth, *pc* the power consumption, *cost* the price of using the link, *cov* the coverage radius and *sec* the security level that the current interface provides. All properties are unified, and thus comparable, values. The property values can be either crisp or fuzzy. For the interface selection algorithm the fuzzy (e.g. very-low, low, medium, high, very-high) values are converted and scaled to crisp values between 0-1 by a linear interpolation.

The vectors (I_i^t) can be combined into a decision matrix $R_{q,p}^t$, where each line is an interface vector I_i^t. Thus the decision matrix is qxp (q = 4, p = 6) matrix with all interfaces and properties, thus it depicts the current state of the links at time *t*. For example, $R_{q,p}^t$ may look like

$$R_{q,p}^t = \begin{bmatrix} 5 & 10 & very\_low & very\_high & low & very\_low \\ 4 & 8.3 & high & high & medium & medium \\ 1 & 0.6 & low & high & low & low \\ 5 & 0.3 & low & high & high & very\_high \end{bmatrix}. \tag{14}$$

Also, each interface has an *enabled* bit, which indicates whether the link in question is enabled or disabled. This informs us whether the interface has satisfied the policy rules or not. In the test cases, an interface is disabled if its signal strength is 1 or below (in a unified 1-5 range). To add a little variability to the simulations, each link has a 20% chance of being in disabled state, in addition to the signal strength rule.

When discussing the tests, $R_{q,p}^t$ represents a decision matrix generated at time *t*. *Time* itself does not count when analyzing the results and actually, during the tests, *t* represents round *t* of a specific test case. One round is a set of semi-random variables representing the current states of the links. Thus, *time* and *round* are used interchangeably. At time *t* a $R_{q,p}^t$ matrix is formed by randomizing properties within technology specific limits.

Because we have six parameters, also the profile needs to have six weights. We analyze each algorithm with two profiles,

w_{data} = [very_high high low low low medium]

and

$w_{mobility}$ = [medium low high medium very_high low].

The first profile emphasizes the data transfer capabilities, such as signal strength and bit rate and the second mobility features, such as power consumption and coverage area. The scaled property values (${r'}_{l,j}^t$) for each MADM method

TABLE 7 Decisions of the algorithms

Algorithm	Rank 1	Rank 2	Rank 3	Rank 4
Signal strength	Ethernet or UMTS		WLAN	Bluetooth
Static priority	Ethernet	WLAN	Bluetooth	UMTS
SAW	UMTS	Ethernet	Bluetooth	WLAN
SPW	UMTS	Ethernet	WLAN	Bluetooth
TOPSIS	UMTS	Ethernet	Bluetooth	WLAN

are made with static scaling between the minimum and maximum values of each property.

At each round, an interface is selected as the *best* by each algorithm. The objective is to study the output of a single round in more detail and then more closely the differences in interface selection outputs and their effects.

One round simulation

First, we study the decisions of all the algorithms with the $w_{mobility}$ profile and decision matrix $R^t_{q,p}$ (where t = 1) presented in equation (14).

The outcome of the algorithms is shown in Table 7. MADM methods provide more accurate results related to the user preferences, which were defined with the profile. However, Ethernet is still ranked quite high due its superior bit rate.

Average bit rate simulation

In the second test, we perform 10000 rounds ($t = 1, \ldots, 10000$) and look at the bit rates provided by the selected interfaces for each algorithm at each round. The w_{data} is used to emphasize the data transfer needs, but also $w_{mobility}$ and $w_{neutral}$ (emphasize none of the properties) are used to study the effect of the set of weights. The output of all of the algorithms are inspected after each round. S^t_a represents the selected interface of algorithm a at round t. The bit rate properties of the selected interfaces are summed up and averaged over all the rounds per algorithm. The Ethernet link (I_1) is manually disabled because of its superior properties compared to the wireless technologies.

The average bit rate results can be seen in Table 8. Figure 21 shows in more detail the bit rates of each algorithm as a function of rounds when using the w_{data} profile. The *Ideal bit rate* refers to an algorithm which always chooses the link with the best bit rate, thus representing the ideal bit rate in each round. The weights clearly have a positive effect, and provide a lot of flexibility for the MADM methods. Of course, the *ideal bit rate* and *static priority* algorithms have very good bit rates, and if it is the only property under interest, these simple algorithms work very well. But, as can be seen the bit rates of the MADM methods are not very far from the ideal, because of the weights. And there are also other properties that

TABLE 8 Average bit rate results (Mbps)

Algorithm	w_{data}	$w_{mobility}$	$w_{neutral}$
Bitrate	13.00	12.89	12.45
Signal strength	7.88	7.62	7.49
Priority	12.99	12.88	12.45
SAW	10.84	2.10	4.85
SPW	11.41	2.20	5.95
TOPSIS	12.28	1.78	6.84

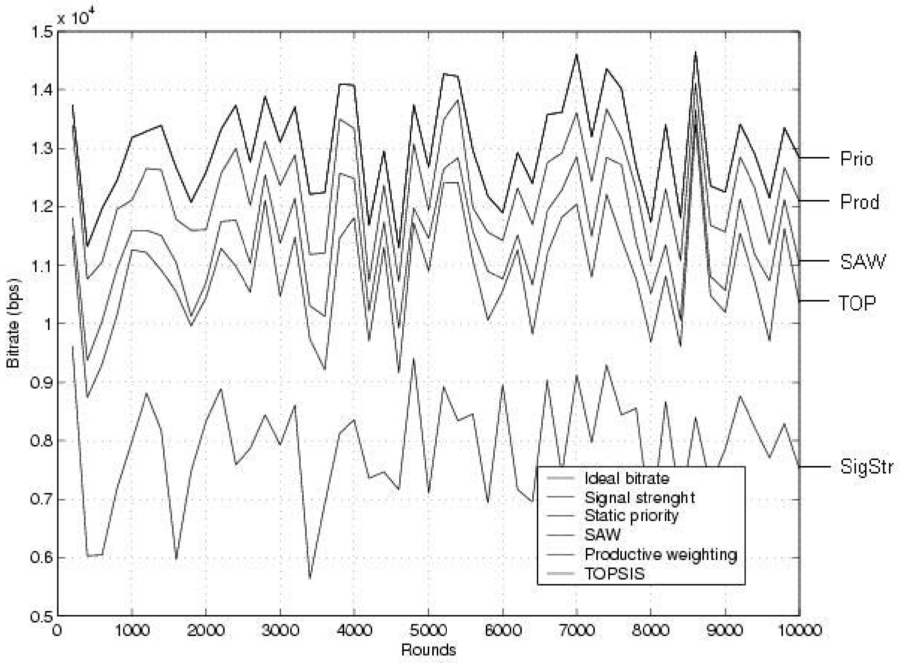


FIGURE 21 Bit rates of the best interfaces for each algorithm

are taken into account with the MADM methods. Table 9 presents the percentage differences of the best interface selection between each algorithm with w_{data} profile.

Algorithm specific goodness

The bit rate simulation showed the results only according to the most preferred property (bit rate). However, there are several properties which have an effect on the interface selection and are weighted by the profile. To analyze more deeply the *goodness* of each algorithm, we calculate the distance of the output of an algorithm (the selected interface) from the ideal solution taking into account all of the properties. The *ideal interface* (or alternative) at round t is defined as

TABLE 9 Differences between the best link selection

Algorithm	SS	PR	SAW	SPW	TOP
Bitrate	0.342	0.015	0.310	0.264	0.156
Signal strenth	xx	0.336	0.181	0.205	0.238
Priority	xx	xx	0.308	0.259	0.153
SAW	xx	xx	xx	0.061	0.170
SPW	xx	xx	xx	xx	0.144

$$S^t_* = (\max_{j=0}^{q} r_{j,1}, \max_{j=0}^{q} r_{j,2}, \ldots, \max_{j=0}^{q} r_{j,p}). \tag{15}$$

It can be said that S^t_* is selected by the *ideal algorithm* (A_*). We define the *difference vector* from S^t_* for algorithm a at round t as the difference of vectors S^t_a and S^t_* as

$$v^t_a = S^t_a - S^t_*. \tag{16}$$

Here, $v^t_{a,j}$ refers to the element j of vector v^t_a. Then we apply a metric on this vector to get a *distance* value. We use Manhattan (i.e. Taxicab) (equation (17)) and Euclidean (equation (18)) metrics.

$$d^{manh,t}_a = \sum_{j=1}^{p} |v^t_{a,j}|, \tag{17}$$

$$d^{eucl,t}_a = \sqrt{\sum_{j=1}^{p} (v^t_{a,j})^2}. \tag{18}$$

Here, $d^{manh,t}_a$ represents the goodness value of algorithm a at round t with the Manhattan metric. Then algorithm a is considered *good* if d^t_a is *small*. In Table 10 the means of d^t_a for each algorithm are shown across all the rounds ($t = 1, \ldots, 10000$). The columns represent the algorithms and the rows the used metrics. In addition to pure Manhattan and Euclidean distances we added the weighted distances, where each distance can be prioritized according to its weight (i.e. w_{data}). It can be seen that the MADM methods have the smallest distance to the ideal solution. Weighting the properties will diminish the distances of the MADM methods, because it emphasizes the property distances.

Combined algorithm performance

Since each algorithm comes up with different distances from the ideal solution, the algorithms could be combined to result in a more effective and flexible solution. Let A^t_b represent the *best algorithm* at round t. A^t_b is defined so that

$$S^t_b \in \{S^t_1, \cdots, S^t_l\} \text{ and } d^t_b = \min_{i \in 1, \cdots, l} d^t_i, \tag{19}$$

TABLE 10 Mean distances with different metrics

Metric	SS	PR	SAW	SPW	TOP
Manh	2.730	3.001	2.746	2.791	2.879
Manh (w)	1.471	1.517	1.445	1.450	1.480
Eucl	1.315	1.367	1.312	1.320	1.341
Eucl (w)	1.017	1.004	0.996	0.993	0.999

TABLE 11 Distance of the combined algorithm

Metric	
Manh	2.432
Manh (w)	1.302
Eucl	1.178
Eucl (w)	0.891

where l is the number of algorithms. The *best interface* S_b^t at round t is defined as the interface selected by A_b^t. We call A_b the *combined algorithm*. It can be proved that A_b always has a smaller than or equal distance to the ones presented in the previous subsection. This fact is represented by equation (20) where r is the number of rounds and l is the number of algorithms.

$$\min_{i=1,l}\left(\frac{\sum_{j=1}^{r} d_i^j}{r}\right) \geq \frac{\sum_{j=1}^{r} \min_{i=1,l} d_i^j}{r}. \tag{20}$$

The combined algorithm is simulated in the same test case as the previous one. Table 11 shows the average distance of A_b with different metrics. It can be seen that the average distances are smaller than the distances presented before in Table 10. It shows that using a combined algorithm in constantly changing heterogeneous environments gives a better result. Due to the simplicity of the presented algorithms, processing power should not be a problem even though several algorithms would be utilized.

3.5 VERHO as a prototype solution

In this section, we present the VERHO interface selection architecture as a prototype solution for mobility management for the 4th generation networks. The VERHO system represents the implementation and playground of all the research work presented in this dissertation.

3.5.1 Architecture

VERHO system is designed to manage available interfaces, links and access points in a multi-interfaced Mobile IP networked device. The system gathers the information of available interfaces (link types, access points, etc.), decides dynamically during run-time about how the interfaces could be utilized best and performs IP handovers utilizing Mobile IPv6.

The system has a cross-layer design, since the goal is to provide link information to interested layers. Figure 22 shows which layers VERHO interacts with [65].

- Extracts link information from network interfaces (Link Layer),
- Controls MIPv6 handovers (Network Layer),
- Applications can utilize information provided by the link layer and the decision engine (Application Layer),
- Users can set their profiles through a Graphical UI and see some statistics from the underlying system.

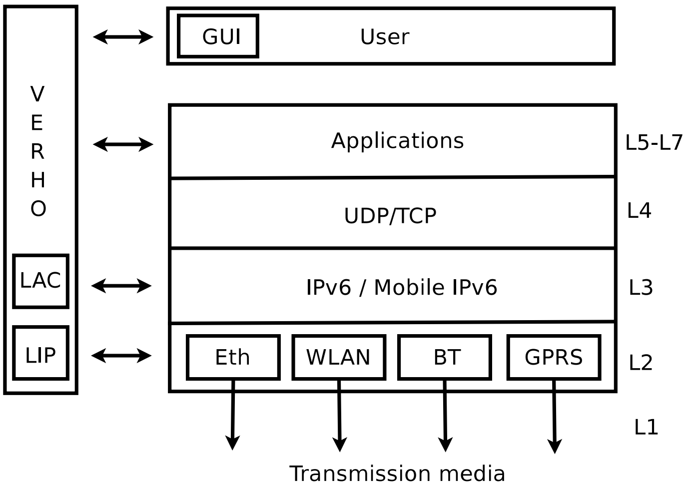


FIGURE 22 VERHO cross-layer interaction

The system consists of several modules and each has a dedicated purpose. Figure 23 shows a high level overview of the architecture. All the components communicate with each other over D-BUS, which is a messaging bus mainly for local Inter-Process Communication (IPC) and Remote Procedure Call (RPC) on a single host.

The core VERHO system consists of the Link Information Provider (LIP) and the Link Access Controller (LAC). The task of LIP is to keep an up-to-date information database about the available links and provide some control functions (e.g. connecting to Access Points). LAC gathers link information from LIP

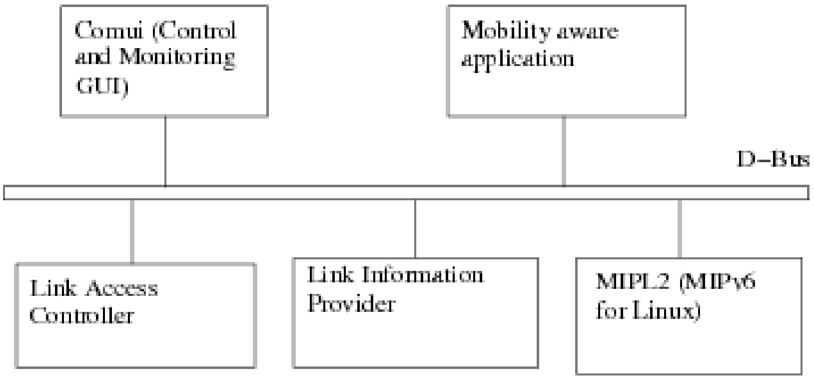


FIGURE 23 VERHO architecture

and makes decisions regarding the usage of available links; moreover, it controls Mobile IPv6 when IP layer handovers are needed to be accomplished.

The system has a GUI for controlling and monitoring purposes and it uses D-BUS to get link information from LIP and to control the system via LAC. Similarly as the GUI, other applications can utilize the features of LIP and LAC. For example, all of the developed prototype mobility aware demonstration applications use LIP and LAC over D-BUS.

From a more technical point of view, the whole system is implemented in a Linux environment. MIPL2 (Mobile IPv6 for Linux v2) [62] is used as the Mobile IPv6 implementation with some D-BUS interface additions. The whole system is developed in user space. The GUI and the demonstration applications are implemented using GTK+, G-Streamer, and Java Media Framework.

3.5.2 Link Information Provider

The task of LIP is to extract information about the available network interfaces and links, according to publication [PX]. This information is then made available over D-BUS for consumption. LIP consists of two main parts, the Link Module (LM) and the Access Point Module (APM). Figure 24 shows a high level architecture overview of LIP.

The Link Module

The LM extracts information from interfaces, thus basically implementing the theory presented in section 3.3. It supports IEEE 802.11 WLAN, Bluetooth, GPRS/UMTS and IEEE 802.3 Ethernet interfaces. Each technology is managed by a separate technology specific submodule and these submodules export a common interface. This way it is easy to extend the system with new access technologies.

LM uses kernel supplied events (via netlink) and polling to gather information. Table 12 shows the different techniques and tools used for the supported access technologies. Link information is provided by two means:

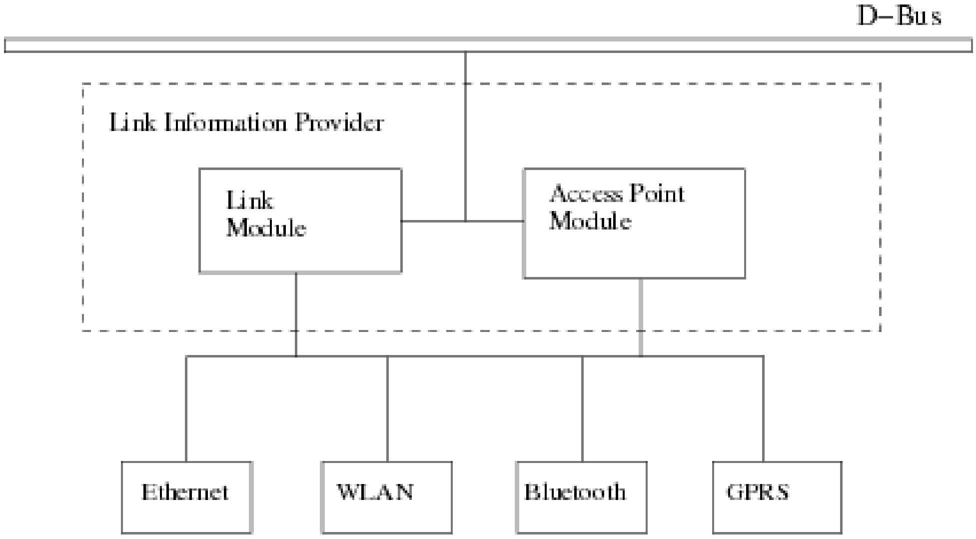


FIGURE 24 High level LIP architecture

- Whenever an event happens in a monitored interface that the LM is capable to listen on or a new interface appears, a signal is sent over D-BUS carrying the new link information.
- Consumers can ask LIP (using Remote Method Invocation over D-BUS) for information on a specific interface or all the interfaces.

TABLE 12 Techniques to get technology specific link information

Access tech.	Technique	
Ethernet	netlink	
WLAN		libiw (Wireless Extensions)
Bluetooth		libbluetooth (Bluez)
GPRS		AT commands

The information provided by each access technology is quite heterogeneous. Even if the same information can be extracted from two different technologies, conversion to a common dimension may be necessary. For this reason the LM provides unified link information for link parameters, in addition to raw link information. Table 13 shows some of the link parameters that are unified by LM. The *Parameter Name* columns show the name of the parameter after unification.

TABLE 13 Unified link parameters

Parameter name	Dimension
Signal Strength	Integer value between 1 and 5
Tx power level	Converted to dBm
Bitrate	Converted to kbps

The signal strength is somewhat special among the information provided by LM. Its value is the source for the *Link Going Down* and *Link Coming Up* indications. It is a dynamically calculated unified value. For WLAN it comes from the SNR, for Bluetooth from Link Quality and for GPRS from Signal Quality. Its range is from 1 to 5 and calculated by dividing the technology specific value (e.g. SNR in case of WLAN) into five ranges. A hysteresis is used to avoid ping-ponging. For more specific information on the classification the signal quality, refer to publication [PX].

Besides providing information, LM helps consumers by indicating what actually caused the signaling of the link information. Table 14 shows some of these indications. Table 15 shows the D-Bus interface of LM, where the link information can be directly polled by methods or automatically informed on event.

TABLE 14 LIP link info indications

Indication	Description
Common	
NewIface	A new interface or interface change
DelIface	Interface disappeared (e.g. removed from the computer)
NewLink	Link established on interface
DelLink	Link deleted on interface
IfUp	Interface administratively disabled
IfDown	Interface administratively enabled
LinkComingUp	The link on the interface is becoming available.
LinkGoingDown	The link on the interface is becoming unavailable.
ChgIfName	Interface name changed
ChgTPL	Tx power level changed
ChgSigStr	Signal strength changed
ChgBitrate	Bitrate changed
ChgRMAC	Remote MAC changed (e.g AP change)
WLAN	
ChgWLANName	WLAN name of interface changed
ChgSNR	SNR changed
ChgEnc	Encyrption got enabled or disabled
ChgESSID	ESSID changed
Bluetooth	
ChgDevID	Device ID changed
ChgLQ	Link Quality changed
GPRS	
ChgSQ	Signal quality changed
ChgBER	Bit error rate changed
ChgPC	Power consumption changed

The AP Module

The AP Module (APM) provides information and controlling facilities for Access Point management. It supports IEEE 802.11 WLAN, Bluetooth and GPRS/UMTS access technologies. Just like LM, APM supports these access technologies via specific submodules in order to make the system easily extensible. Also, the technologies to access the link layer are the same as with LM. AP information is also heterogeneous and varies between access technologies. Table 16 shows the various information provided by the APM.

APM manages an AP list for each supported access technology. AP information is sent to consumers in the same two ways as for LM, thus on request and events. Such changes can be

- New AP appeared
- AP disappeared
- AP state changed

APM provides also control over the connection initiation and teardown for the controlling entity (e.g. LAC). This way the controlling entity can also manage the horizontal (i.e. intra-technology) handovers, taking the responsibility of the technology specific handover mechanisms. Table 17 shows the D-Bus interface of APM.

TABLE 15 LM D-Bus interface

Name	Description
Methods	
GetLinkInfo	Get information on a given interface
GetLinkIndices	Get the list of the indices of the available interfaces
Signals	
LinkInfoChanged	Link information changed.

TABLE 16 AP information

Access Tech.	AP Information
WLAN	ESSID, MAC addr, channel, bitrate, noise, signal quality
Bluetooth	AP name, MAC addr, Link quality, Tx power level
GPRS	AP name, IP protocol

3.5.3 Link Access Controller

The logic of the VERHO system resides in the Link Access Controller (LAC). LAC consumes LIP (LM and APM) information and controls MIPv6 handovers. The modifications for the MIPL implementation has been kept at a minimum level to support easy code portability to other MIPv6 implementations and mobility management protocols (e.g. MIPv4, HIP).

LAC manages a single list of all the interfaces. Each interface is assigned three flags and a preference value. The flag can indicate

- Interface state – Enabled or disabled.
- Preference Value calculation – Automatic or Manual.
- Interface state management – Automatic or Manual.

If the interface state is *Disabled*, the interface is not allowed to be used by MIPv6, i.e., no CoA on the interface can be registered with the HA or CNs. By default, LAC manages the interface state automatically, that is, it enables and disables according to specific events. The events can be provided by LIP, GUI or some other external application. This represents the policy control presented in section 3.4.1.

Preference values for interfaces are calculated by LAC dynamically, and they change due to changing link information. Just like interface state management, preference value calculation can also be managed manually by some outside party (e.g. user and operator profiles).

At any point in time, the interface with an *Enabled* state and the highest preference value is chosen to be registered with the HA and CNs by MIPv6. In

TABLE 17 APM D-Bus interface

Name	Description
Methods	
APGet	Get the list of available Access Points. Takes the access technology as an argument (e.g. WLAN).
APConnect	Connects to the given Access Point.
APDisconnect	Disconnects from the given Access Point.
Signals	
APNew	New AP appeared.
APDel	AP disappeared.
APChange	AP information changed.

case where there are several available connections with similar properties, a hysteresis or extra interface specific priorities might be good to avoid ping-ponging. Table 18 shows the D-Bus interface of LAC as informative purposes to show the existing capabilities of the controlling entity.

TABLE 18 LAC D-Bus interface

Name	Description
Methods	
GetPrefVal	Get preference value of interface.
SetPrefVal	Set preference value of interface.
GetState	Get state of interface (enabled/disabled).
SetState	Set state of interface.
GetWeight	Get the weight vector of the active profile.
SetWeight	Set the weight vector of the active profile.
RecalcPrefVals	Force the re-calculation of the interface preference values.
DoHandover	Select an interface manually.
GetCurrIface	Get the currently active (selected) interface.
GetProfiles	Get the available profiles.
GetProfile	Get one specific profile.
SetProfile	Set the parameters of a given profile.
GetActiveProf	Get the active profile.
SetActiveProf	Select the active profile.
Signals	
PrefValChanged	Preference Value changed of the interface.
StateChanged	State changed of the interface.
HandoverStarted	Handover started to the interface.
ActiveProfileChanged	The selected profile has changed.

Preference Value Calculation

Preference values are calculated using a Simple Additive Weighting MADM method already presented in the MADM algorithms section 3.4.2. This method fits very well the purpose of choosing among interfaces by taking into account multiple interface characteristics.

LAC uses the unified link information provided by LIP (shown in Table 13) to make its decisions. Each link characteristic is assigned a weight which describes the importance of the given characteristic. A *weight vector* consists of a weight for each characteristic and defines a Profile. An outside party can supply or change profiles on-the-fly. Profiles can represent e.g. user demands, in which case the outside party is the user. The controlling interface (see Section 3.5.4) is used to define and activate user profiles.

The weighted average is calculated by the equation (21).

$$pv_i = \frac{\sum_{j=1}^{p} w_j * r_{i,j}}{\sum_{j=1}^{p} w_j}, \tag{21}$$

in which the preference value of interface i is pv_i, w_j is the weight of characteristic j and $r_{i,j}$ is the value of characteristic j for interface i. Any other MADM method could be implemented also, e.g. TOPSIS or MEW.

LAC recalculates the preference value of an interface upon LIP events or on user request by getting the current active profile and the current values of the link characteristics belonging to the interface and executes the weighted average calculation. The interface with the highest preference value is selected and if it is different then the current active interface MIPL2 is informed about the change via D-BUS. The end result is a MIPv6 handover to the selected interface.

3.5.4 Controller and monitoring GUI

Comui is the controlling and monitoring interface for the VERHO system. It is a graphical interface developed with the GTK+ toolkit and is available for the Maemo [58] platform. The main purposes of this GUI is to let the user provide his preferences to the VERHO system (i.e. polices and profiles). Also, the Comui provides the user information of the available links and their utilization.

The monitoring interface

Comui can be used by users to see information about the available network interfaces in the MN. The graphical interface shows a list of the available network interfaces (see Figure 25). The currently active interface is highlighted. For each interface the interface name, type, rank, bitrate and AP name are shown in columns. The user can get more detailed information about the interfaces in a separate window (see Figure 26).

The controlling interface

With Comui, the user can control the following aspects of the system. Figure 27 shows the profile management screen.

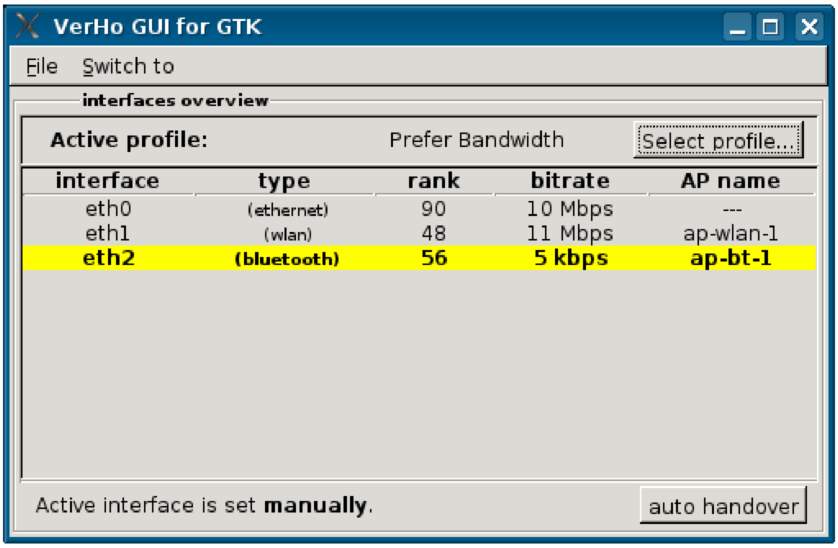
- Manage profiles: select active profile, add new profile, delete existing profile.

- Enable and disable interfaces manually.

- Specify preference values manually.

- Select the currently active interface manually.

- Select the currently used Access Point for a given interface manually.

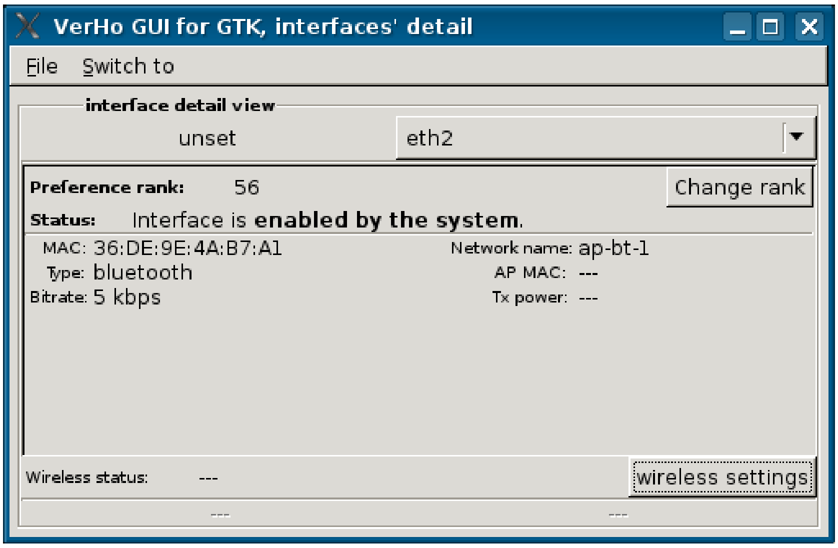


Active profile: Prefer Bandwidth

interface	type	rank	bitrate	AP name
eth0	(ethernet)	90	10 Mbps	---
eth1	(wlan)	48	11 Mbps	ap-wlan-1
eth2	**(bluetooth)**	**56**	**5 kbps**	**ap-bt-1**

Active interface is set **manually**.

FIGURE 25 The interface list of Comui



unset eth2

Preference rank: 56

Status: Interface is **enabled by the system**.

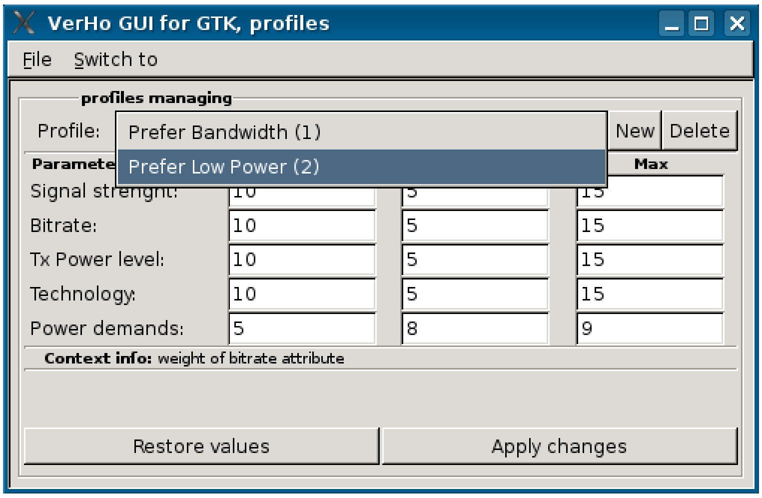
MAC: 36:DE:9E:4A:B7:A1
Type: bluetooth
Bitrate: 5 kbps

Network name: ap-bt-1
AP MAC: ---
Tx power: ---

Wireless status: ---

--- ---

FIGURE 26 The detailed interface information window of Comui



Profile: Prefer Bandwidth (1)
Prefer Low Power (2)

Paramete			Max
Signal strenght:	10	5	15
Bitrate:	10	5	15
Tx Power level:	10	5	15
Technology:	10	5	15
Power demands:	5	8	9

Context info: weight of bitrate attribute

FIGURE 27 The Profile management window of Comui

Interface state, preference values, selection of the active interface and the selection of the used AP is done automatically by LAC in the default case. Thus LIP gathers the real-time link layer information and LAC calculates the best available interface by using user profiles and SAW MADM method. When the user manually instructs LAC via Comui to set any of these parameters LAC stops managing them automatically. To revert to automatic mode the user has to specify that explicitly.

3.5.5 Prototype Applications

The VERHO system can be used to develop mobility aware applications. A mobility aware application can use the provided information for example to adapt to the current link characteristics. Information provided by VERHO includes

- Link information from LIP (LM),
- Access point information from LIP (APM),
- Handover indications from LAC.

In the following sections we look at some of the developed prototype mobility aware applications.

Multimedia streamer

The Multimedia Streamer (MS) consists of a client and a server. MS functions as an example of End-to-End adaption, where the adaptation procedures themselves are performed in the content server. Both the client and the server are implemented in Java. The client integrates the image, audio and video playing functionalities and the server supports audio and video streaming. For the camera stream, a dedicated webcam was used as the server (see Figure 28).

Streaming of the multimedia content is done by using Real Time Protocol (RTP) and Real Time Control Protocol (RTCP), and Real Time Streaming Protocol (RTSP) is used for controlling the playing process (e.g. requesting the proper stream quality during adaptation).

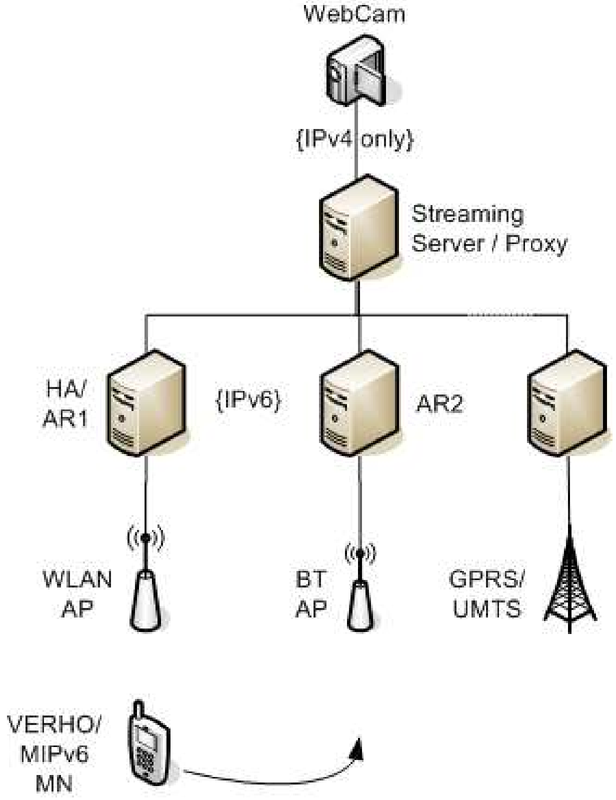


FIGURE 28 The multimedia streamer network

The player runs on the MN and it is made mobility aware by listening to LIP and LAC information. The player, based on the capabilities of the active interface, requests the proper stream quality from the server. Whenever the player receives information form LIP and LAC, it re-evaluates the validity of the current stream quality with regards to the active interface. If not valid, the player requests the proper quality from the server.

Camera streamer

The camera used is Axis 2100 and it supports only IPv4 networks. Due to the fact that the VERHO system operates only in IPv6 [3], we needed to develop an IPv6-IPv4 proxy. The proxy is implemented in Java and its sole purpose is to relay the camera stream between IPv6 and IPv4 realms.

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[3] Due the fact that VERHO is currently implemented on top of Mobile IPv6 for Linux (MIPL), which supports only IPv6. However, as VERHO is designed to be as independent as possible from the mobility management system, one should be able to change it to another mobility management system with a small effort.

The camera uses HyperText Transfer Protocol (HTTP) to transfer the images. It can transmit both motion JPEG and still images in various image qualities. The different image types and qualities are accessible by using CGI requests via HyperText Markup Language (HTML) GET destined for the web server running on the camera itself. The camera serves the purpose of a streaming server and no separate server implementation is needed.

Audio streamer

The server contains several audio files that can be requested by the client. Each audio file can be delivered with various qualities. During adaptation the client requests a certain quality and the server starts streaming the same audio file in the requested quality from the position where the last stream was stopped.

Video streamer

Unlike the audio streamer, the video streamer server supports pre-defined classes of qualities (for e.g. Ethernet, WLAN and GPRS). A video content is prepared for all the supported classes as a separate video file. When the client requests a specific quality the server maps this request to a class and starts streaming the selected video file. During adaptation, the newly selected video file starts streaming from the position where the previous video stream left off.

IP-TV streaming

The IP-TV is similar to the Media Streamer. Figure 29 shows the topology of the client/server model of the IP-TV. We have divided the operations to the content, network, access and end-devices. Content providers provide only the content with good quality to the customers. Network operators provide the adaptation services as well as digital rights management, etc. Access operators provide accesses of different technologies to the consumers. VERHO device is just one device consuming the IP-TV service tailored for the physical restrictions of the device as well as software and access requirements and end users' preferences.

The TV stream is received from a terrestrial digital TV broadcast network. This stream is made available on an IP network via multicast (one multicast channel per TV channel). In the network, a node acts as an Adaptation Proxy (APr). The APr has joined the multicast IP-TV stream and can provide different MPEG4 quality classes of the TV stream. In addition to adaptation, APr performs the conversion from the IPv4 to IPv6 and multicast to unicast for the clients. Mobile clients request the stream from the APr by indicating their quality requirements, which are provided by VERHO. [4]

When a mobile client needs a different quality (e.g. due to moving to a different access technology), it informs the APr about its new requirements. The

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[4] In practice, the adaptation should be transparent, thus the service is requested from the content provider.

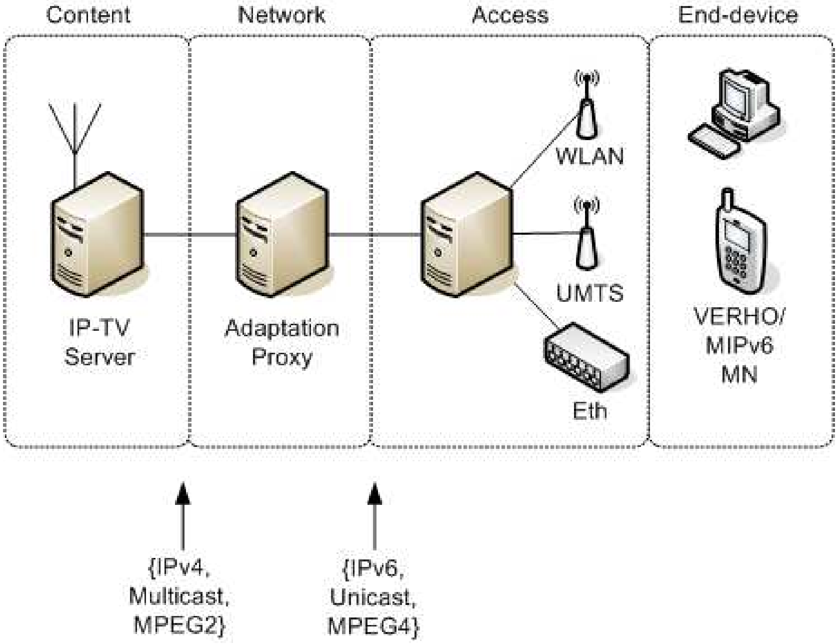

FIGURE 29 The IP-TV test network

APr, upon receiving the request, maps the request of the client to a supported quality class and starts streaming the adapted content to the client.

3.6 Enhancements and further research

In this section, we discuss some possible enhancements to VERHO system, and how it could be enhanced and improved.

3.6.1 Additional parameters from network

The available bandwidth in IEEE 802.11 is dependent of the number of wireless stations associated to the AP and their data flow amount. It is impossible for the station to acquire this information without changes to the infrastructure. The price of using an AP is also quite a complicated issue because of the problem of how the MN could get the price information in a dynamic way (i.e. not predefined price/Wireless Internet Service Provider). In [56] it is shown that the price and available bandwidth information could be added to link layer beacon messages (e.g. IEEE 802.11). Also the IP subnet information of the AR could be added to the beacon messages. The Reference [34] suggests that the available bandwidth could be evaluated from the IEEE 802.11 MAC layer by listening and collecting the Network Allocation Vector (NAV). However, the problem with these is that they are access technology dependent solutions. For them to work independently from the access technology, some upper layer technology is needed.

Currently VERHO gathers information from the link layer to the technology dependent parameters as well as AP information. But these functions let the system know about mostly static or semi-static (configurable) parameters of the APs. Only the signal strength value informs the system of constantly varying radio channel. Information such as available bandwidth of an AP or AR would be extremely valuable for interface and AP selection procedures. However, this information is currently not available through standard link layer procedures; it requires IP or upper layer communication.

The link technologies enable only one active connection to the AP, which is mostly used by the applications. It is possible to receive only link layer information (i.e. beacons) from the other neighboring APs, even though the APs would have perfect knowledge of their current status and services. By Layer 3 protocols, such as Simple Network Management Protocol (SNMP), these services could be polled from the Management Information Bases (MIBs) of the AP. However, without breaking the current connection to the AP and establishing a new connection to the new AP, there is no way of accessing this information directly. [5]

Candidate Access Router Protocol (CARD) [57] has been developed for the purpose of gathering information from the neighboring environment. CARD functions in IP layer and provides functionalities for gathering interface selection related information from the neighboring ARs. CARD relies on network support to gather the information from the environment. MN utilizing CARD only sends the L2 identifiers of the neighboring APs to its default AR by a specific signaling protocol. The network has to form itself a picture of the environment and L2Identifier - L3IP pairs. The network needs to know what APs are connected to which ARs (i.e. AP with a certain L2 identifier is paired to a certain AR with an IP subnet). CARD signaling can also include information such as the available bandwidth and price.

Positioning systems are increasing their popularity while, at the same time, the amount of location aware applications is increasing. VERHO could benefit from Global Positioning System (GPS) or other similar system in controlling the AP scanning. The aim is to keep an interface active and scan only if necessary to minimize power consumption. In [89] the authors discuss the usage of positioning information for generating triggers for handover procedures.

3.6.2 Transport layer issues

Traditional transport protocols, such as TCP and UDP, have been designed for wired environment. In wireless environment they have problems related to the constantly changing radio link quality and mobility. For example, TCP has been identified with the following problems that can cause a quite low throughput:

- Bandwidth limitations
- Long round-trip times

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[5] This is possible if using two interfaces of the same technology, or if the technology supports simultaneous connections to several APs.

- Random transmission losses
- User mobility
- Power consumption

Since the massive growth of wireless technology use, there has been a lot of research related to transport layer protocols. Especially for TCP, several enhancements and modifications have been proposed [85].

- Link layer solutions – TCP-aware link layer protocols such as the Snoop protocol [8], buffer the segments destined to the MN and provide fast retransmissions in the radio link.
- TCP modifications – TCP algorithms are modified to overcome wireless link specific problems, e.g. Selective Acknowledgements TCP (SACK TCP) [60], Indirect TCP (I-TCP) [7] and M-TCP [13]. The latter two are based on a principle, where the End-to-End TCP connection is split up into a wireless and wired part.
- New transport protocols – This category includes new TCP protocols such as the transmission rate based Wireless TCP (WTCP) [99].

In addition to improving the traditional transport layer protocols, completely new protocols have been introduced to the transport layer, including Stream Control Transmission Protocol (SCTP) [123] and Datagram Congestion Control Protocol (DCCP) [53].

Transport protocol development is out of scope of this dissertation. Nevertheless, VERHO could probably utilize the Transport Layer protocols and Transport Layer protocols could benefit from VERHO. Connection oriented transport protocols, such as TCP and SCTP, constantly control the transmission rate to offer fair and reliable use of the transmission path. Thus these protocol in a way measure the instantaneous End-to-End bit rate, even though the measurement happens on the basis of transmission errors. However, the connection oriented protocols could be utilized in providing some estimate (i.e. hint) from the available bit rate. VERHO has the knowledge of the real-time link status and quality, thus VERHO could be utilized in Transport Layer providing the link information to link layer aware transport protocols. This way VERHO could control the transmission rate of a transport protocol to minimize retransmissions.

3.6.3 Ensuring Quality of Service

Ensuring Quality of Service (QoS) is really important as all services and access technologies are changing towards IP transport. When the load in the network increases, flow based priorization is needed to ensure the QoS for e.g. real time services. Quality of Service has been extensively studied for IP core networks, and architectures such as Differentiated Services (DiffServ) [12] and Integrated

Services (IntServ) [122] have been standardized for some years now. DiffServ offers per-aggregate QoS without any user specific reservations in a DiffServ domain while IntServ offers per-flow QoS by using e.g. Resource Reservation Protocol (RSVP) as a specific QoS reservation signaling. Also, in wireless technologies the Quality of Service features are becoming quite mature.

Quality-of-Service (QoS) supported IEEE 802.11e was standardized a year ago. IEEE 802.11e employs a new MAC protocol called the Enhanced Distributed Co-ordination Function (EDCF). The problem with WLAN networks is the high error rate probability, which can rise up to 40% causing difficulties especially to the streaming type of applications. IEEE 802.11e standard is trying to correct the situation by enabling the use of a maximum of eight separate priority queues for prioritizing higher priority traffic compared to other traffic. Also, IEEE 802.16 [43] (WiMAX) offers QoS differentation with five application classes.

The 3rd Generation Cellular Systems offer packet switched QoS by introducing four traffic classes: Conversational class for voice and Real Time multimedia messaging, Streaming class for streaming types of applications (e.g. Video On Demand), Interactive class for interactive types of applications (e.g. eCommerce, WEB browsing) and Background class for background type applications (e.g. email, FTP). In addition, each traffic class can use several priority classes using Allocation and Retention Parameters (ARP).

However, to ensure the End-to-End QoS, the whole path between the sender and receiver must be QoS capable. QoS management should be IP-based, requiring some QoS mappings between IP and technology specific link layers. Problems arise due to the differences in QoS mechanisms of different access and core technologies.

3G and WLAN interworking studies

We have studied the inter-operability of 3G and IEEE 802.11e wireless networks and the suitability of DiffServ and IntServ core networks to provide efficient End-to-End QoS control in wireless communication systems in publication [PXII]. The throughputs, delays and dropping rates have been studied with QoS mapping and both core networks. Also the effect of wireless channel error rates to throughputs while changing the traffic mix and average packet sizes of an individual traffic class is studied.

All traffic can be handled by mapping it into one or several IEEE 802.11e queues depending on the user or flow characteristics. The mapping process can be policy based controlled and the mapping can be indicated at the IP level by the DSCP (DiffServ Code Point) inserted to the TOS (Type-of-Service) field by DS classifier/marker mechanism or by the actual application that generates the control plane traffic. Table 19 shows the PHB (Per Hop Behaviour) actions with DSCP mappings.

The simulations have been performed with ns-2 [80] using IEEE 802.11 EDCF extensions. The packet transmission errors in the radio channel have been modeled with a two-state Markov model. Simulations have been performed in three

TABLE 19 3G Traffic class mapping into DSCP

Traffic class	PHB actions (mapped into DSCP)
Conversational	EF
Streaming	AF 1
Interactive (THP1)	AF 21
Interactive (THP2)	AF 22
Interactive (THP3)	AF 23
Background	AF 3

separate environments to be presented here shortly. Details of the simulation environment and the rest of the results can be found in publication [PXII]. In this dissertation only a glimpse of these results are presented due to a lack of space.

1. One access point simulation case – Four terminals with different priorities connected to one access point.
2. End-to-End simulation case – Two one access point scenarios connected with a DiffServ core network.
3. RSVP DiffServ comparison case – 18 one access point scenarios connected with both DiffServ and IntServ core networks resulting in total of 72 terminals.

In all cases, one access point has four terminals connected. Of these two carry Constant Bit Rate (CBR) traffic of 2.5Mbps and two Variable Bit Rate (VBR) traffic of 2.5Mbps. Packet sizes of the traffic classes are varied by iterating through all the packet size combinations between 100 and 1500 bytes using six 200 byte steps. The possible packet sizes are thus 100, 300, 500, 700, 900, 1100, 1300 and 1500 bytes. The iteration process is as follows: at the iteration round 0 packet size of all classes is 100 bytes. The lowest priority traffic class packet size is increased by 200 bytes at every iteration. If the packet size is 1500 bytes, it is reset to 100 bytes, the next lowest traffic class packet size is increased by 200 bytes, and so forth.

As an example of the results the throughput results with 20% channel error rate in each simulation scenario have been presented in Figures 30, 31, 32 and 33. One access point scenario consists of only the WLAN radio interface QoS, presenting the QoS features of IEEE 802.11e (Scenario 1). Clearly the EDCF can differentiate the different priorities. In the End-to-End simulation scenario (Scenario 2) the IEEE 802.11e to DiffServ DSCP mapping has been performed. However, the results are quite similar to the one access point scenario due to the fact that the DiffServ core did not get overloaded from the simulated traffic. The RSVP and DiffServ comparison simulations (Scenario 3) have been performed a large environment, where the load affected by the terminals exceeds the capacity of the core network. In this situation the RSVP protocols seem to ensure also the QoS of the lower priority classes a little better than DiffServ.

The following conclusions can be made from the simulation results:

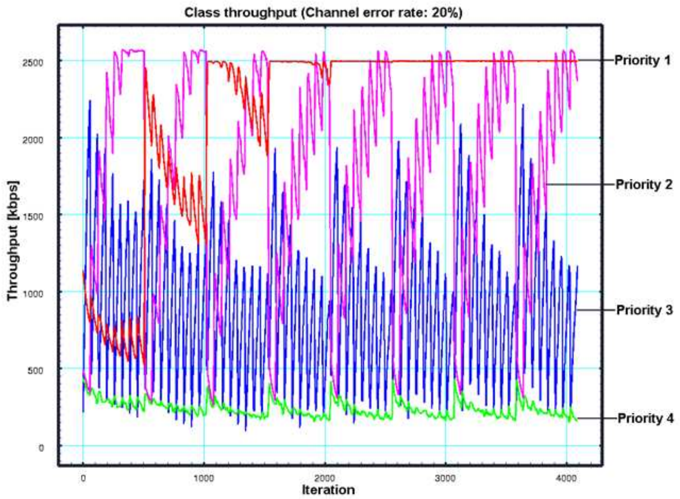

FIGURE 30 Throughput in relation to packet size combination iteration in one access point scenario with 20% channel error rate

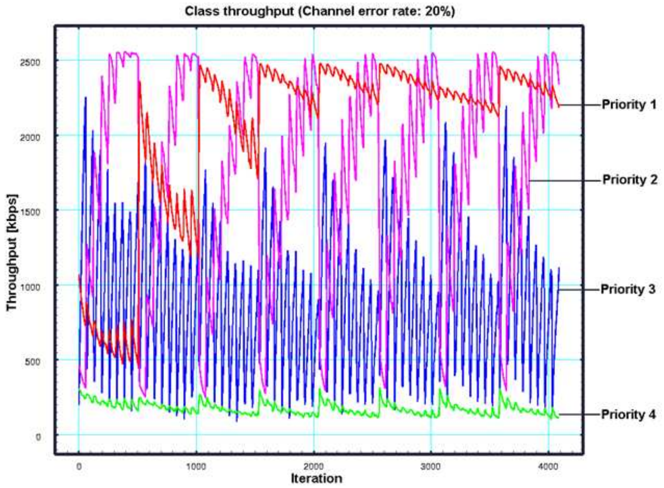

FIGURE 31 Throughput in relation to packet size combination iteration in End-to-End scenario with 20% channel error rate

- IEEE 802.11 EDCF works well with different channel error rates being suitable for controlling QoS in 3G/WLAN interworking scenarios.

- The need for classification (service differentiation) increases with channel error rate.

- Best packet size for optimal throughputs vary depending on traffic class as well as on the channel error rate.

- Best option for QoS control would be RSVP IEEE 802.11e because RSVP core network can ensure better QoS to smaller priority traffic in high load conditions.

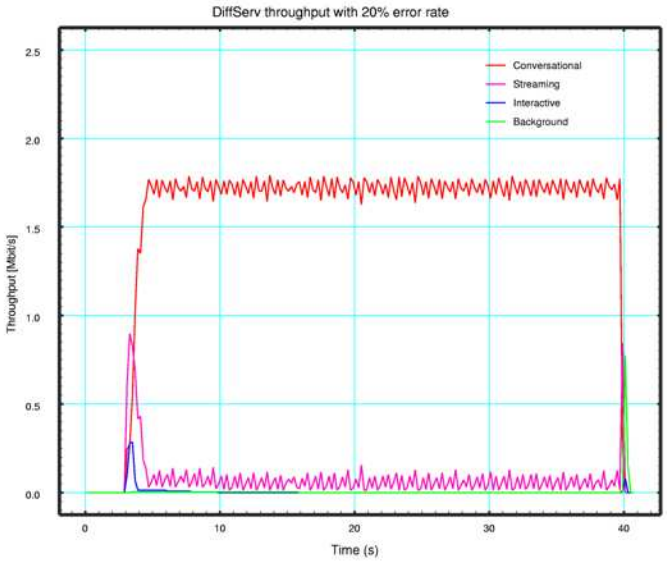

FIGURE 32 Throughput in relation to packet size combination iteration in DiffServ core scenario with 20% channel error rate

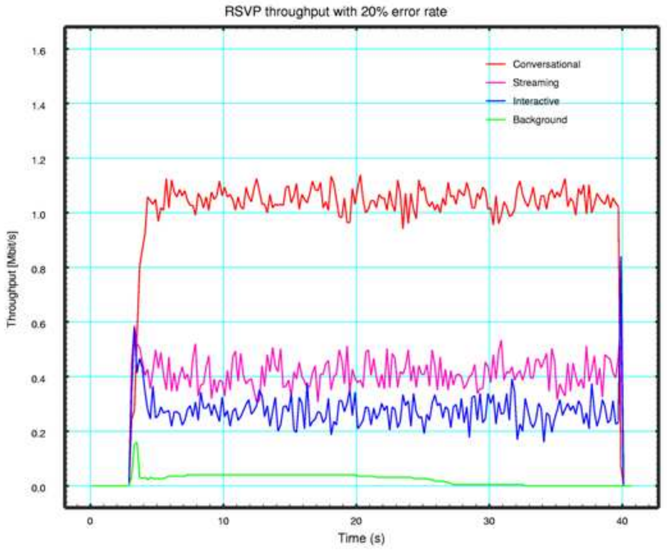

FIGURE 33 Throughput in relation to packet size combination iteration in IntServ core scenario with 20% channel error rate

The mobility is not considered in these simulations, thus all terminals were always connected to the same Access Point. Mobility brings other interesting research problems to the combining the mobility related and QoS related problems. In case of IntServ, the RSVP signaling need to be re-negotiated in handover cases, because the reservations use the CoA as the end point. With DiffServ renegotiation is not needed, just the link layer and IP layer QoS mapping. Next, the Quality of Service management with VERHO system is discussed.

Ensuring QoS with VERHO

Mobile IPv6 handles the mobility in a transparent way to the applications, but in addition to that, the existing QoS reservations should be preserved while changing Point of Attachments (i.e. performing horizontal or vertical handovers). The QoS negotiation needs to be bound to a CoA which informs about the current location of the MN. While a handover is made with Mobile IPv6, the CoA changes. Thus, the QoS needs to be re-negotiated to address the new End-to-End path between the end nodes.

VERHO system knows the real-time state and quality of the links and is also in control of the handover target interface, link and handover timing. A natural step would be to evolve VERHO to include also the QoS negotiation signaling. In [18] the authors present a generic architecture for End-to-End QoS heterogeneous networks. The EWQoS reference model is presented in Figure 34. The architecture consists of

- Quality of Service Domain Agent (QDA) – handles network resources within a single wireless network domain.
- Quality of Service Agent (QSA) – allows the CNs to adapt to QoS requirements of the MN.
- Quality of Service Mobile Agent (QMA) – interfaces with the QDA to maintain seamless QoS during handovers. It manages the wireless interfaces that the MN has, as well as the connections with the networks that are involved in the handover process. It also implements the End-to-End signaling with the QSA.

The EWQoS uses the Next Generations in Signaling (NSIS) [36] Signaling Layer Protocol (NSLP) for Quality of Service signaling. Each QoS-NSLP node along the reservation path implements the QoS Model of the underlying system, whether it is the wireless access technology or DiffServ core.

The QMA includes the Mobility Solution as well as the Network Discovery modules. The VERHO system implements similar functionalities in the LIP and LAC modules while utilizing the Mobile IPv6 protocol. VERHO could control, in addition to the mobility management, the QoS reservation requests and signaling.

3.6.4 Simultaneous multiple access

According to [71] IPv6 and Mobile IPv6 have the following unresolved issues related to multihoming:

- Path selection
- Ingress filtering
- Failure detection

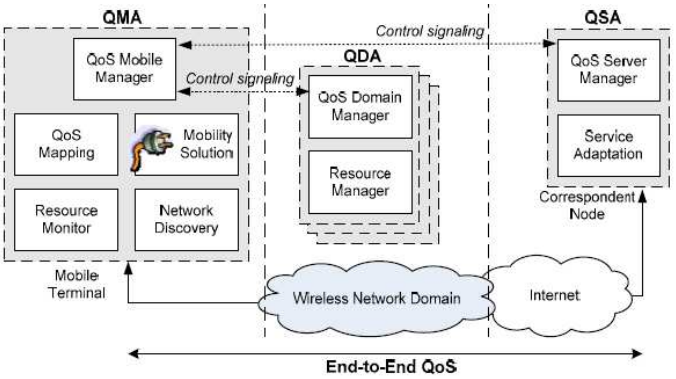

FIGURE 34 EWQoS reference model [18]

- Binding multiple CoAs to a given HoA
- Simultaneous location in home and foreign networks

Due to limitations of the Mobile IPv6 protocol, only one interface can be active at a time (i.e. registered to the HA). This is mainly caused by the fact that Mobile IPv6 [46] does not specify a way to register multiple CoAs with the same HoA at the peers (e.g. HA or CN). Thus there is a need of enhancing Mobile IPv6 to support multiple interfaces or to design a completely new protocol. In [68] the authors discuss several ways of achieving multihoming with Mobile IPv6.

- Utilizing several HAs and HoAs - each of the MN's interfaces has a separate HoA (and respectively a HA). This approach enables horizontal handovers, vertical handovers as well as simultaneous access. Horizontal handovers are handled in the same way as in [46]. Vertical handovers can be performed on HoA basis binding the address of the new interface (IF2) to the HA1 of the old interface IF1 (i.e. HoA1 - CoA2 binding in HA1). Also, dividing the applications between the interfaces on HoA basis (applications utilizing HoA1 -> use IF1, applications utilizing HoA2 -> use IF2, etc). This kind of approach has been utilized for example in [126].
- Per-CN mobility - MN can use Mobile IPv6 to register different CoAs with different CNs to spread its flows from different CNs on different interfaces. According to [46] direct communication between MN and CN is possible through Route Optimization. MN can send BU to CN, which has also MIPv6 support and thus is capable of holding bindings. MN can this way choose which CoA (i.e. interface) the CN is using in Route Optimization. In choosing the interface some kinds of policy tables can be utilized, for example, based on application types.
- Per-flow mobility - Mobility is handled for each flow independently. Each flow can be uniquely identified (e.g. addresses, ports, protocol number) and redirected between interfaces without modifying binding of other flows.

This requires new Binding Update options for sending flow level bindings. Also modifications to the binding cache are needed due to a need to hold several HoA - CoA bindings depending on the flow. An example of these kinds of mobility solutions can be found in [114] and [68].

- Load balancing mobility. This is the finest grain of mobility, where each packet can be routed through different interfaces.

The IETF Monami6 working group [67] is building a specification for multiple CoA registration. Since the peers have to know how to select the correct CoA when sending packets to the MN, the working group is also constructing a specification for flow binding distribution. A flow binding is an association between a flow and a CoA. The packets described by the flow are sent to the associated CoA of the MN. With multiple CoA registration and flow binding distribution it becomes possible to control the usage of the available network interfaces in a finer grain than the current VERHO system does (i.e. per-flow basis).

The Monami6 draft [115] specifies an extension to Mobile IPv6 to enable it to register multiple bindings with the same HoA and with different CoAs simultaneously. The basic idea is to identify bindings with a Binding unique Identifier (BID). This BID is carried in a BU message in a new sub-option. The BID is stored in or assigned to both Binding Update List (BUL) entries and Binding Cache (BC) entries. The BID uniquely identifies a binding of a HoA. Having a BID, a binding can be updated (e.g. when CoA is changed) by sending a BU carrying the BID identifying the binding to be changed. Having registered multiple CoAs per HoA is only a part of the story. There has to be a mechanism to tell which packets should be sent according to which binding.

The logic of the VERHO system is located in the LAC module. This module assigns a preference value to each network interface and selects the one with the highest preference value. Due to the limitations of Mobile IPv6 VERHO supports only one active interface at a time. The next step of VERHO is to transform it from an interface manager to a multihoming manager. This requires extensions to Mobile IPv6 (e.g. MultiCoA) and a way of utilizing the applications requirements in creating the flow bindings.

3.7 Summary

In this chapter the Mobile IPv6 functionality and performance has been presented in heterogeneous access environment. Pure Mobile IPv6 has some problems mainly related to the interface selection to support the Always Best Connected connection to the user and applications. We discuss the usage and benefits of real time link layer information in improving handover functionality. The interface selection procedure with policies and Multiple Attribute Decision Making algorithms is presented. Different MADM algorithms are also analyzed by means of Matlab simulations. VERHO mobility management system architecture is presented together with some adaptive applications that can benefit from VERHO. Finally, some enhancements to improve the VERHO system are discussed.

4 CONCLUSIONS AND FUTURE RESEARCH

In this dissertation we have presented the research challenges that upcoming 4G converging networks bring up. These include wireless system discovery, interface selection, mobility and location management, security, End-to-End Quality of Service, etc. We have mainly focused on solving the mobility management in the 4G converging networks, especially enhancing the Mobile IPv6 handover performance to enable seamless (i.e. low delay and minimal packet loss) connections and interface selection of Mobile IPv6 and thus to enable Always Best Connected access to the user.

In practice we proposed a Flow-based Fast Handover for Mobile IPv6 (FFHMIPv6) to reduce the CoA signaling delay of Mobile IPv6. Especially, when using Route Optimization, the signaling delays of Mobile IPv6 might become quite high due to extra BU signaling as well as security procedures (i.e. Return Routability) to all CNs. Also, the uplink enhancements for FFHMIPv6 enable the uplink data traffic before the signaling procedures are finished to the HA. Fast handovers for both directions are especially important for conversational traffic such as Voice over IP. Simulative and real network analysis shows that the FFHMIPv6 is capable of providing the CoA registration phase in hierarchical network environments. But in heterogeneous multi-access environment the FFHMIPv6 might not bring that many benefits because the Crossover Router is not found. However, in this case the FFHMIPv6 falls back to MIPv6 functionality providing a similar handover performance.

Heterogeneous environments call for more intelligent handover control than the pure Mobile IPv6 can offer. To offer Always Best Connected access to users and applications, real-time knowledge of the constantly changing radio environment is needed, including link status and quality related information as well as services that can be offered through distinct links. The way of gathering and utilizing technology specific link layer information in handover context is discussed. User preferences are also taken into account in interface selection by means of profiles (i.e. set of weights). Interface selection is performed according to several input parameters. Several Multiple Attribute Decision Making algorithms for interface selection purpose were also analyzed by means of simulations. The

MADM algorithms are flexible in constantly changing environments and with different kinds of user preferences. The VERHO mobility management system architecture is presented is practice.

While VERHO has the knowledge of the links, this information can be utilized also for different purposes, including application content adaptation. Here we present two different solutions for VERHO aided content adaptation as examples: streaming on demand and IP-TV. VERHO enables real-time stream size adaptation (e.g. resolution, refresh rate) based on current link quality, which might change with the load situations or vertical handovers. In addition to mobility management, efficient QoS mapping between access technology dependent QoS mechanisms and IP core network QoS architectures (i.e. IntServ, DiffServ) are there to ensure true End-to-End Quality of Service to different flows.

Several future work ideas were already presented at the end of both main Chapters 2 and 3. The most essential ones are itemized next.

- Additional parameters to be taken into account in the interface selection process, e.g. price and available bandwidth parameters. Both of these could be gathered using the CARD protocol, and the latter could be achieved by enhancing the technology specific MAC layer or cross-layer interaction with the transport layer.

- New interface selection algorithms can be invented and analyzed by means of simulations or, in practice, within the VERHO system. More complex algorithms instead of just one selection equation might provide more flexibility.

- Integrating QoS signaling functionality into VERHO system and testing the resulting agent in a real DiffServ/IntServ core network.

- Taking into use Multiple CoA registrations for Mobile IPv6 and thus changing VERHO into a multihoming manager induces research challenges, such as how the applications can provide their demands in order to VERHO provide them with the proper interface.

- VERHO is designed to be independent from the mobility management protocol. Porting VERHO to some Mobile IP implementation (e.g. Dynamics Mobile IP) would create more practical testing possibilities for todays' IP networks.

- As positioning information plays an important role in the context-aware applications, it is expected that the positioning technologies will be integrated to cellular phones in a short while. Thus, positioning information could be researched as an input to VERHO mobility management.

YHTEENVETO (FINNISH SUMMARY)

Tämä väitöskirja käsittelee liikkuvuuden hallintaa IP-pohjaisissa langattomissa verkoissa. Liikkuvuus monimuotoisessa langattomassa ympäristössä voi aiheuttaa sekä tekniikan sisäisiä että käytettävän tekniikan valintaan liittyviä yhteysvastuun vaihtoja. IETF:ssä on kehitetty Mobile IP protokolla sekä sen IPv6-versio liikkuvuuden hallinnan ratkaisemiseksi IP-verkoissa. Vaikka Mobile IPv6 hallitsee sovelluksille näkymättömät yhteysvastuun vaihdot, sen käyttöönotto vaatii vielä useiden ongelmien ratkaisua. Tässä väitöskirjassa keskitytään lähinnä yhteysvastuun vaihdon viiveen minimoimiseen sekä parhaan liitynnän valintaan monimuotoisissa langattomissa ympäristöissä.

Tutkimuksissa on kehitetty Mobile IPv6 yhteysvastuun vaihdon rekisteröintiviiveen pienentämiseen pystyvä laajennos nimeltään Flow-based Fast Handover for Mobile IPv6. Menetelmällä rekisteröimisviivettä ja täten myös pakettien hävikkiä voidaan pienentää selvästi. Yhteysvastuun vaihtoon kuluva aika ei ole riippuvainen liikennöintikumppanien välisistä etäisyyksistä. Tämän lisäksi olemme tutkineet menetelmää, jolla Mobile IPv6 yhteysvastuun vaihtoja voidaan hallita siten, että käyttäjällä ja sovelluksilla olisi aina käytössään sen hetken paras yhteys. Liitynnän valinnassa otetaan huomioon liityntöjen reaaliaikainen tila ja laatu sekä käyttäjän vaatimukset. Kehitellyillä menetelmillä tarjotaan käyttäjälle paras yhteys ja saumattomat yhteenvastuun vaihdot.

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